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(54) **TUBE LUMINESCENT RETROFIT USING LIGHT EMITTING DIODES**

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F21V 5/04   (2006.01)
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F21Y 101/02   (2006.01)
F21Y 103/00   (2006.01)

(52) **U.S. Cl.**
CPC *F21V 7/0066* (2013.01); *G02B 6/0073* (2013.01); *F21S 8/04* (2013.01); *F21V 5/04* (2013.01); *F21W 2131/402* (2013.01); *F21Y 2101/02* (2013.01); *F21Y 2103/003* (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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(57) **ABSTRACT**

The invention relates to a LED-based optical unit including a LED disposed on a surface and a monolithic module encompassing the LED and including a re-directing portion and a first diffusing portion. The first diffusing portion is configured to diffuse light incident thereon. The re-directing portion is configured to re-direct at least a first portion of light emitted by the LED to be incident on the first diffusing portion.

14 Claims, 24 Drawing Sheets
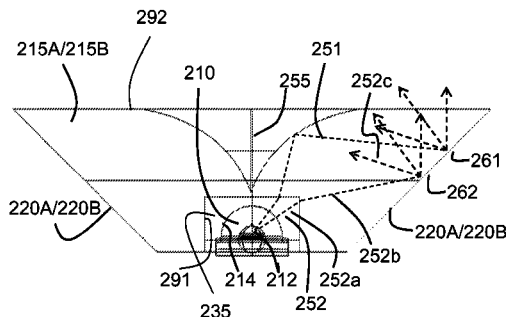
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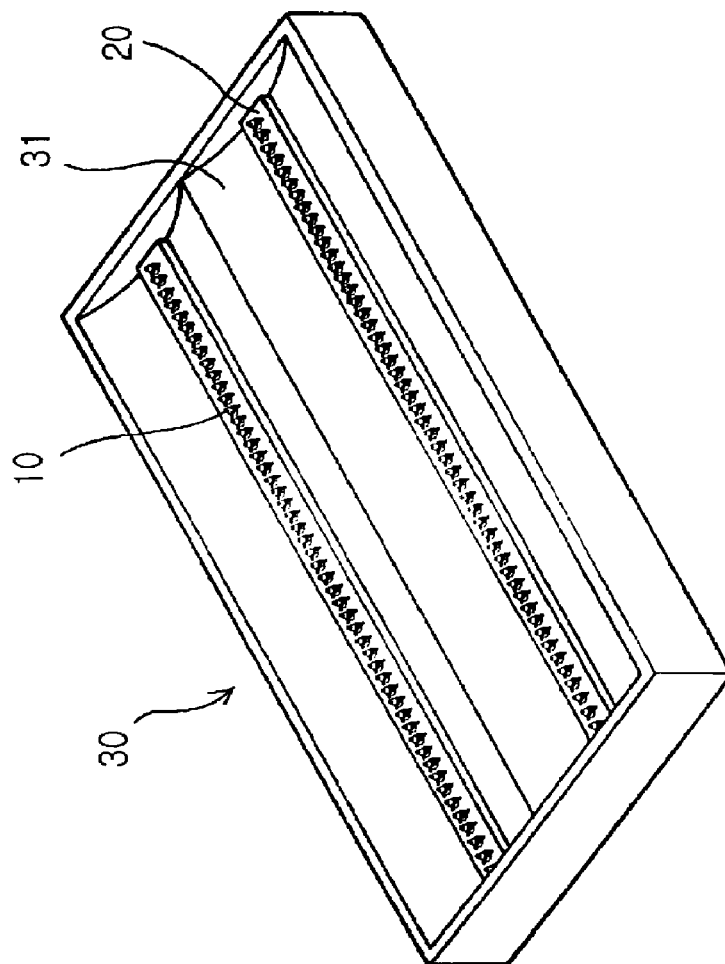
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FIG. 1 (PRIOR ART)
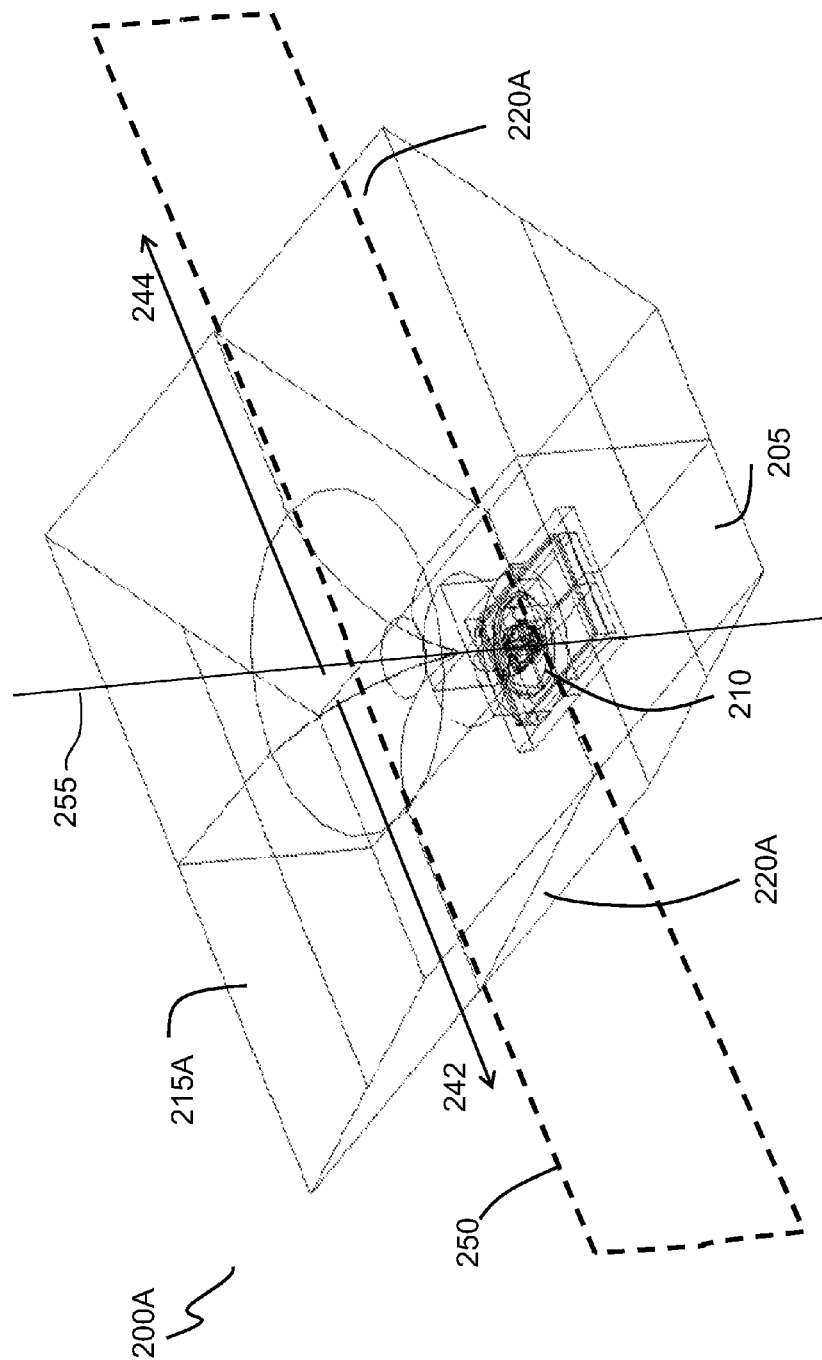
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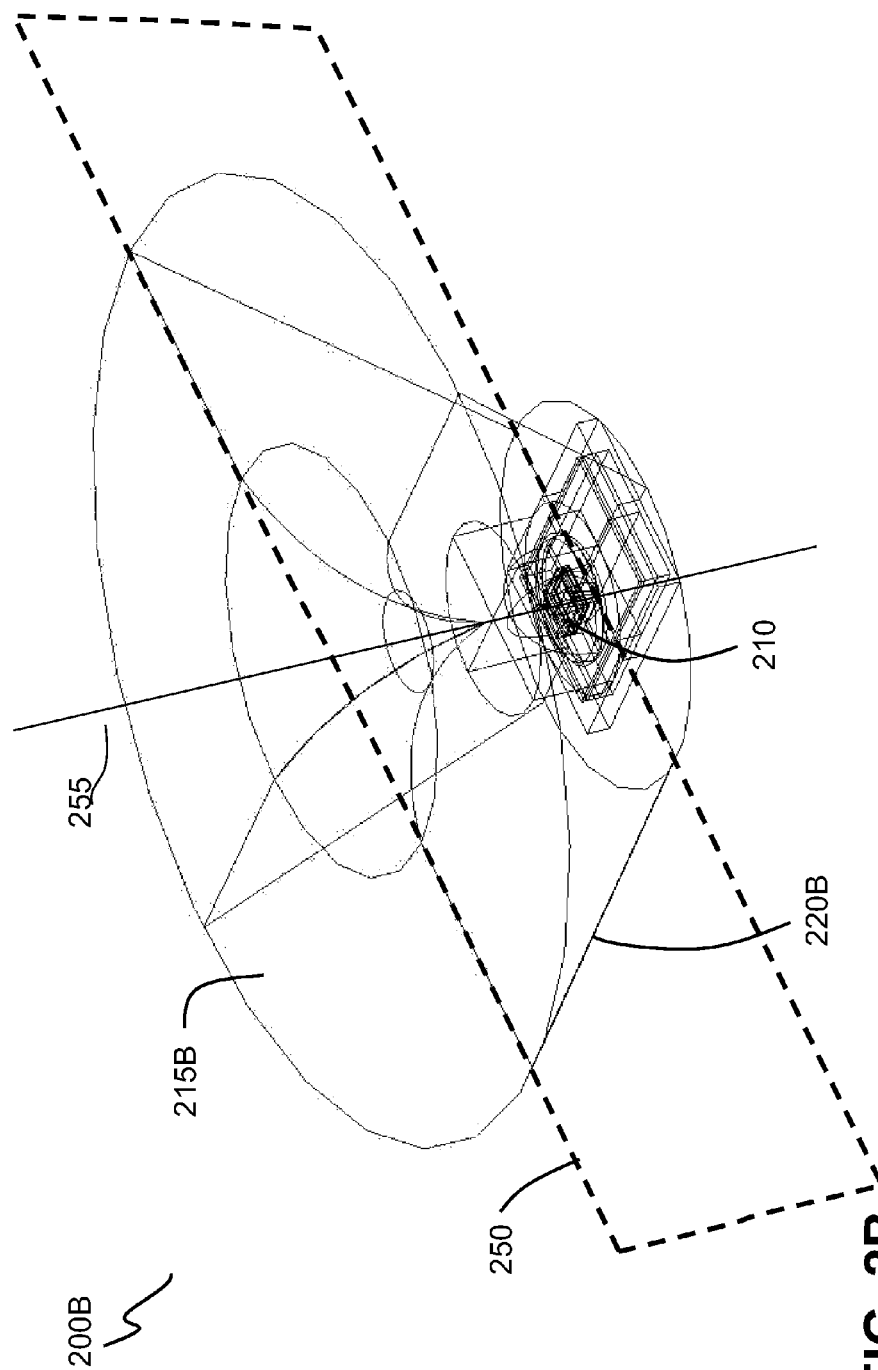
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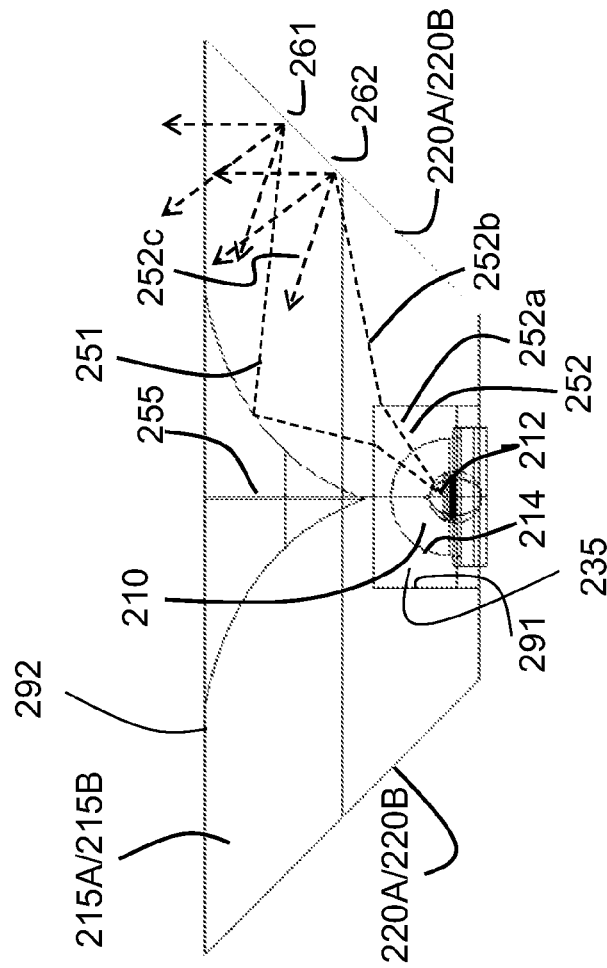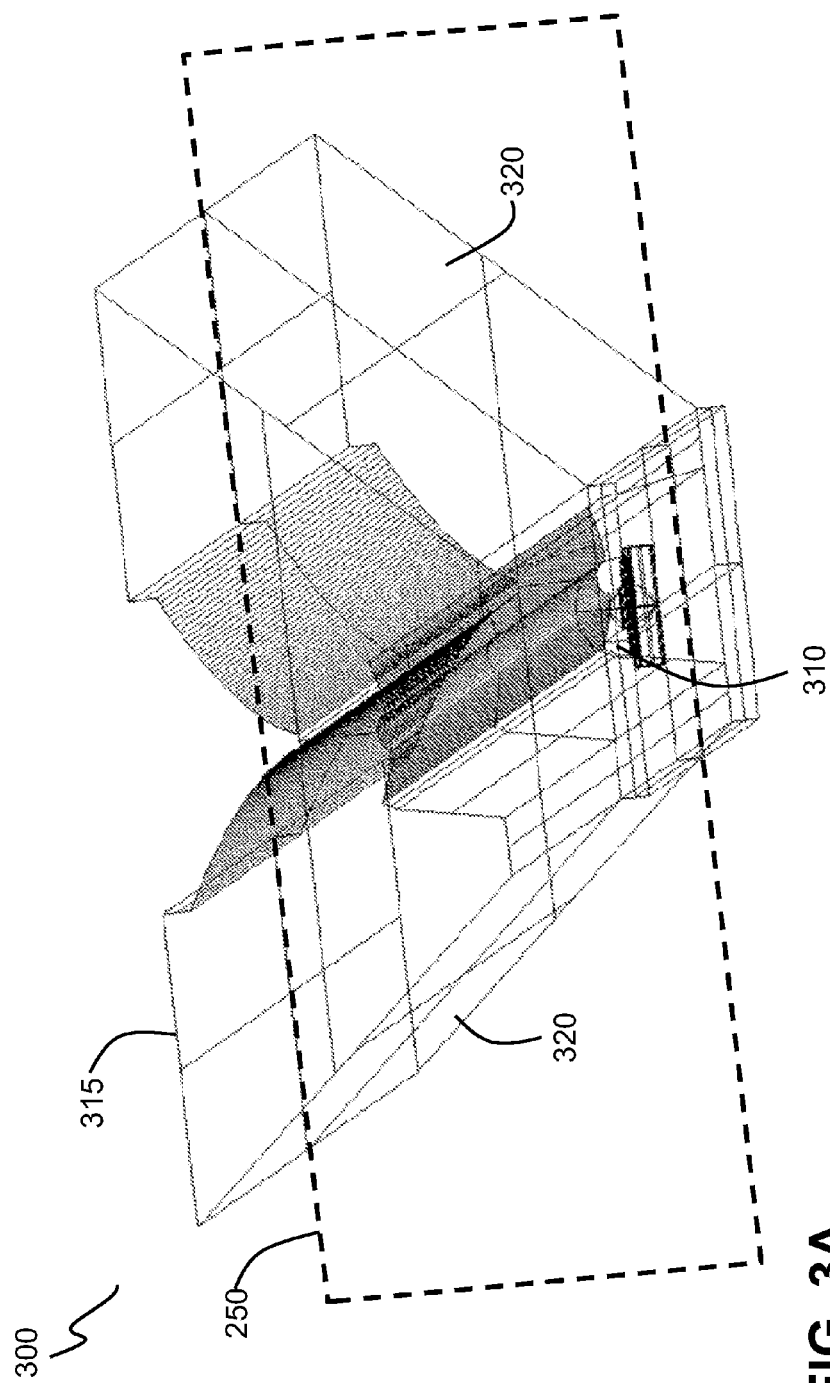
255

215B

210

250

220B

FIG. 2B

FIG. 2C

300

315

250

320

320

310

FIG. 3A

FIG. 3B

210/310

400A

200A / 300

405A

FIG. 4A

210/310

400B

200A / 300

405B

FIG. 4B

210

400C

200B

405C

FIG. 4C

FIG. 4E

FIG. 4D

FIG. 4F

400F

315

310

FIG. 4G

510

550

550a

520

570

530

540

580

580

FIG. 5 (PRIOR ART)

600

692

651

651c

651b

651a

638

635

615

614

612

610

639

691

FIG.6A

600

692

651

651c

651b

651a

638

635

630

614

612

610

691
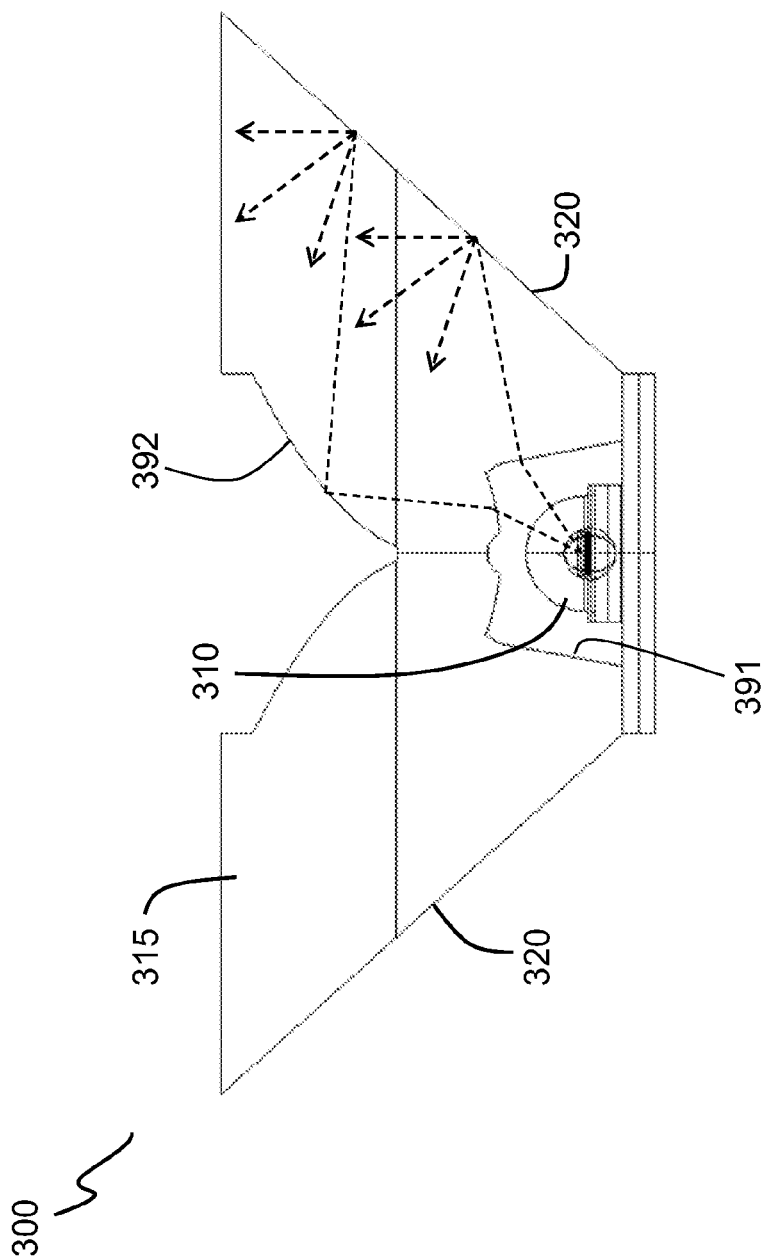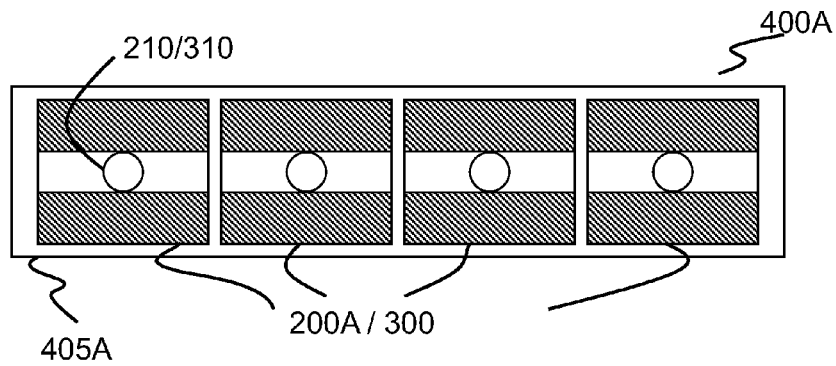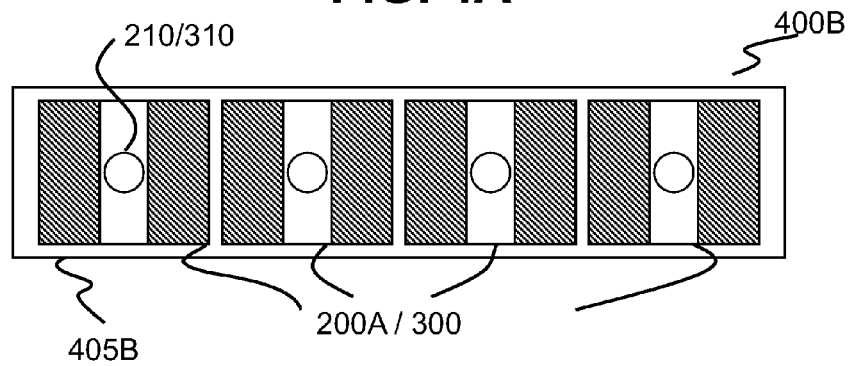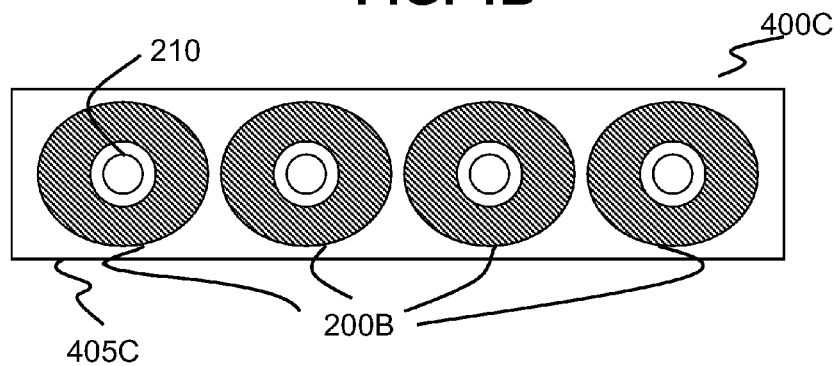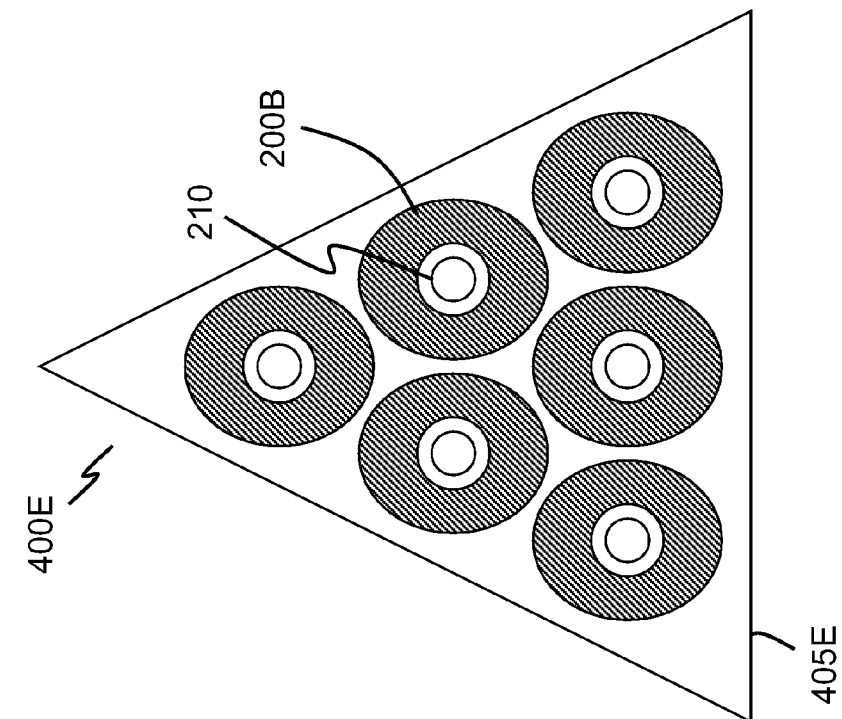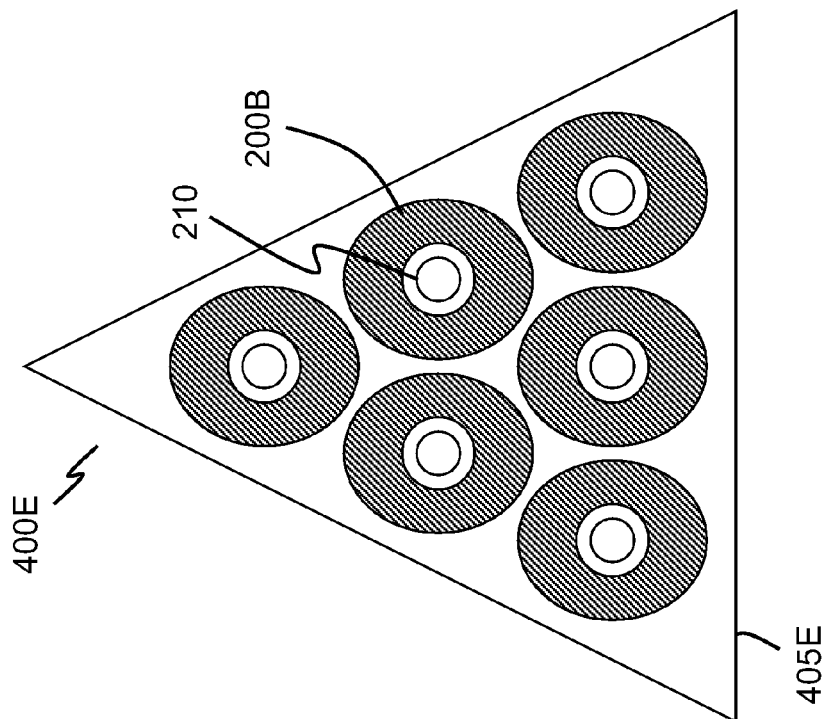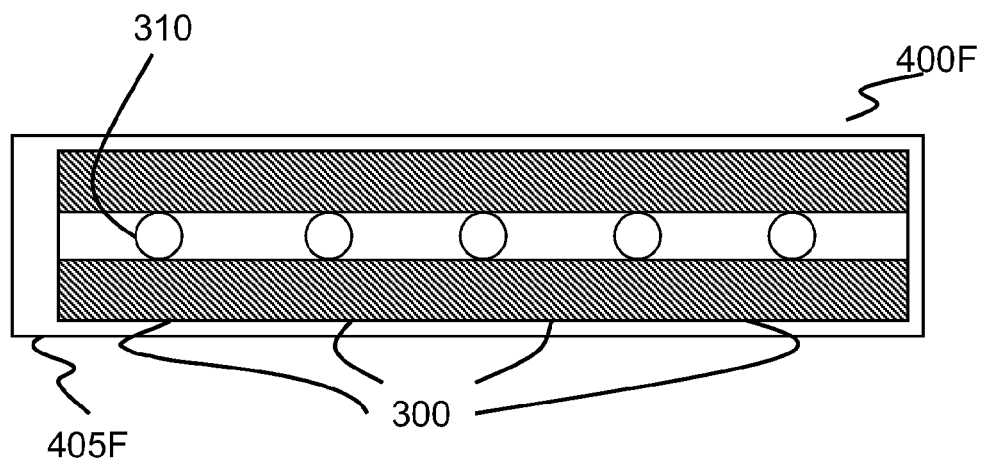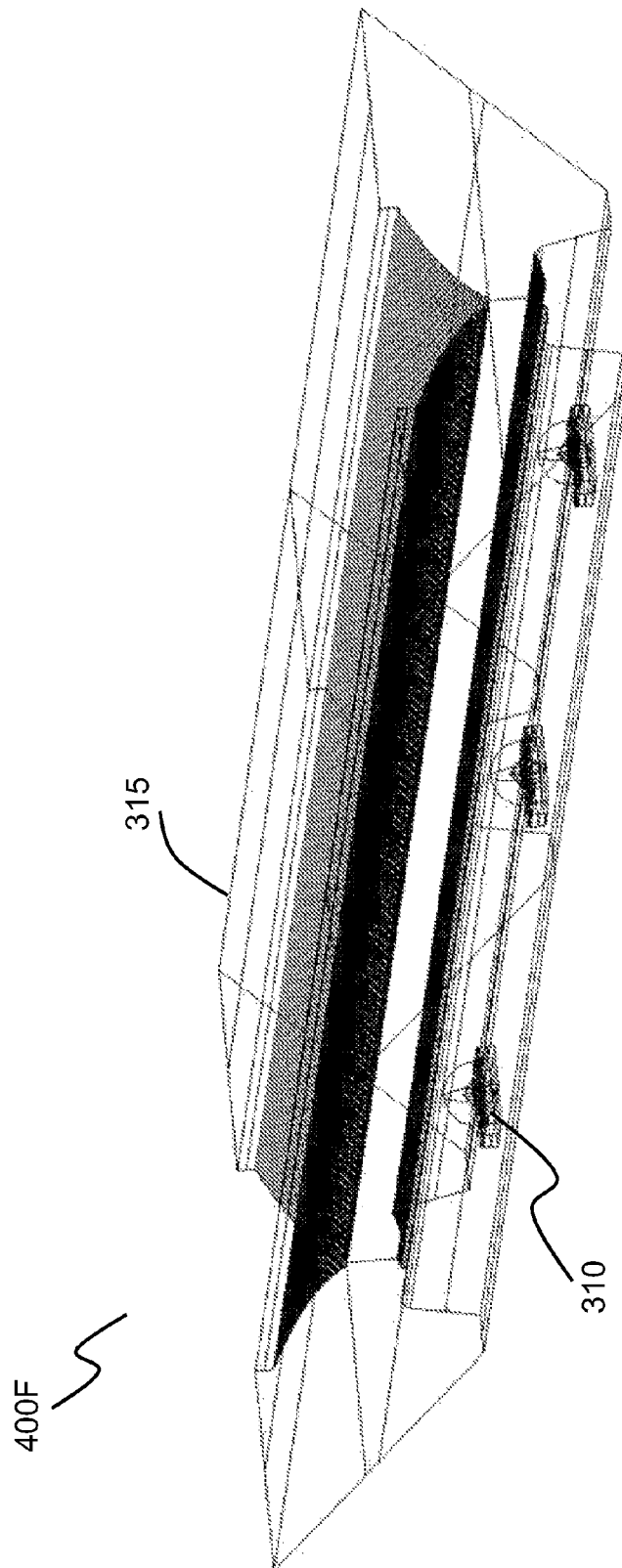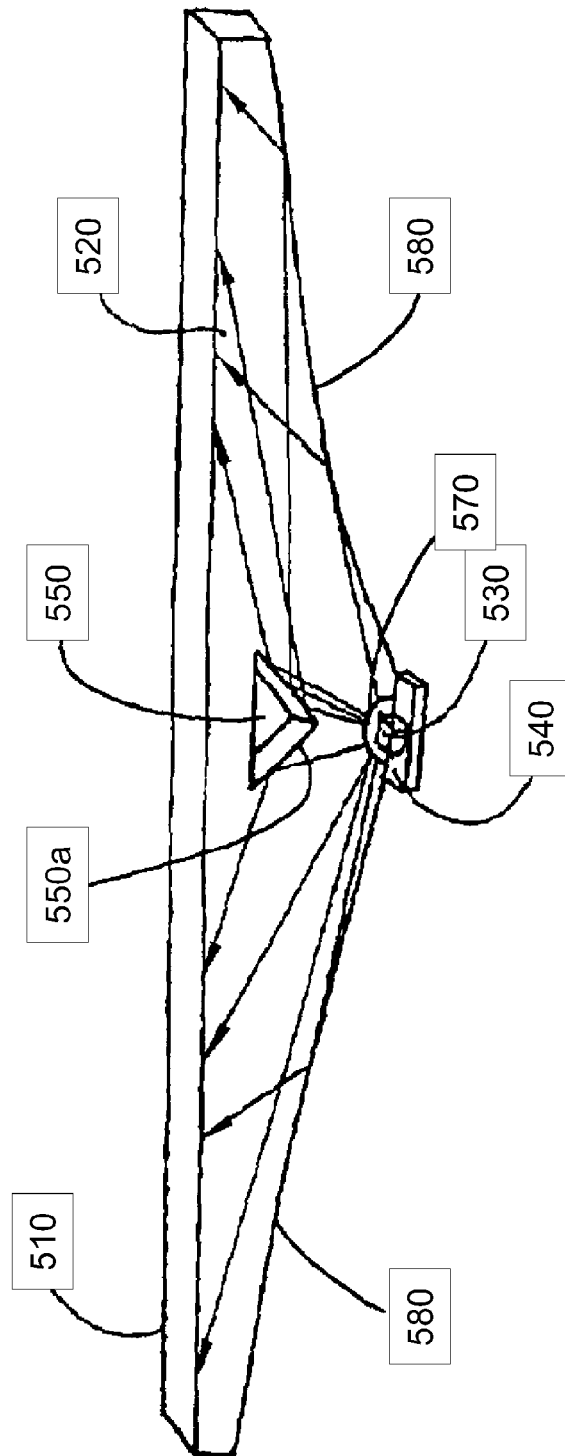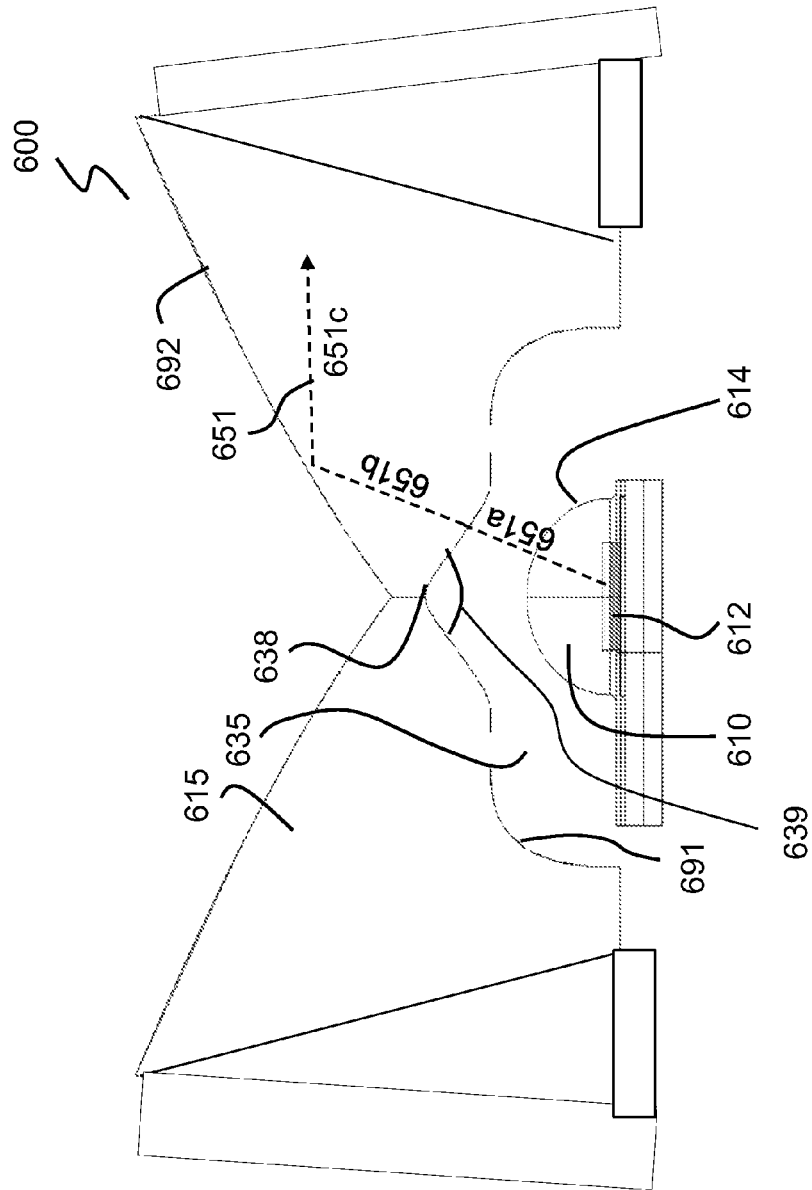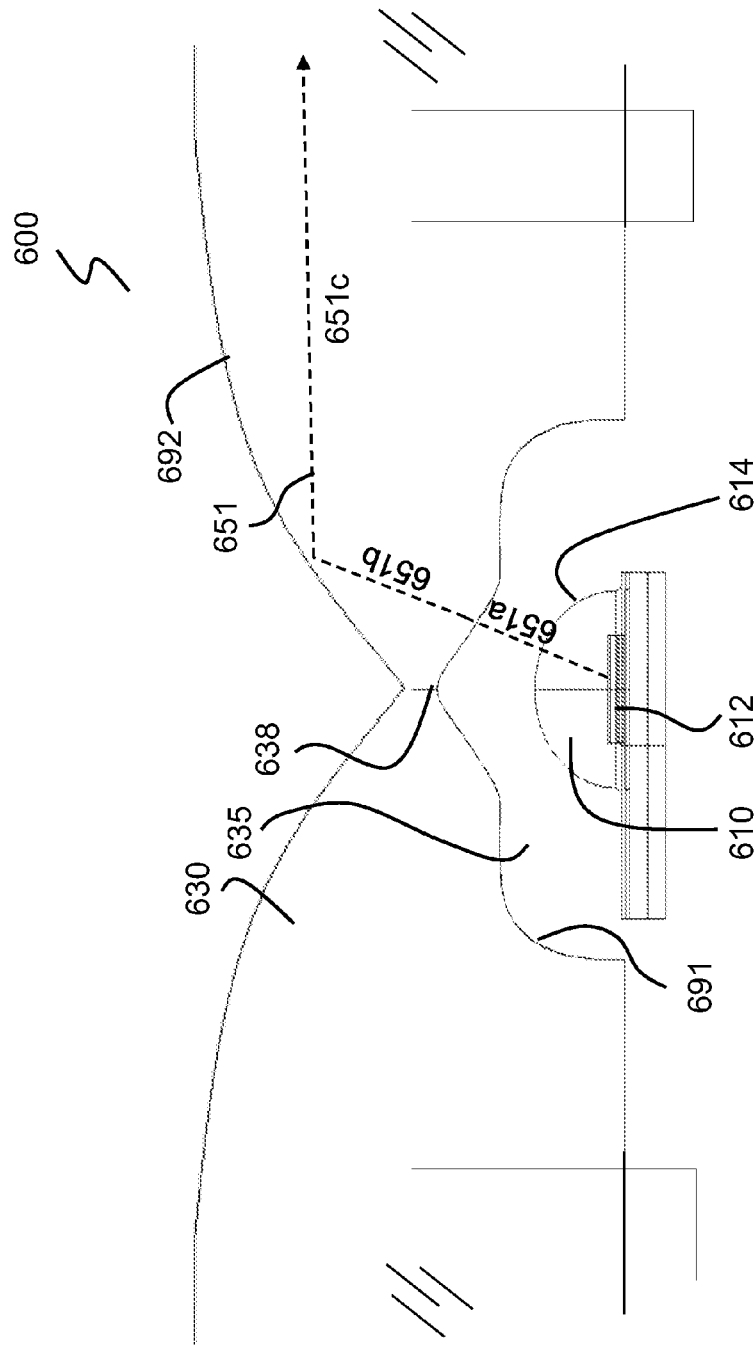
FIG.6B
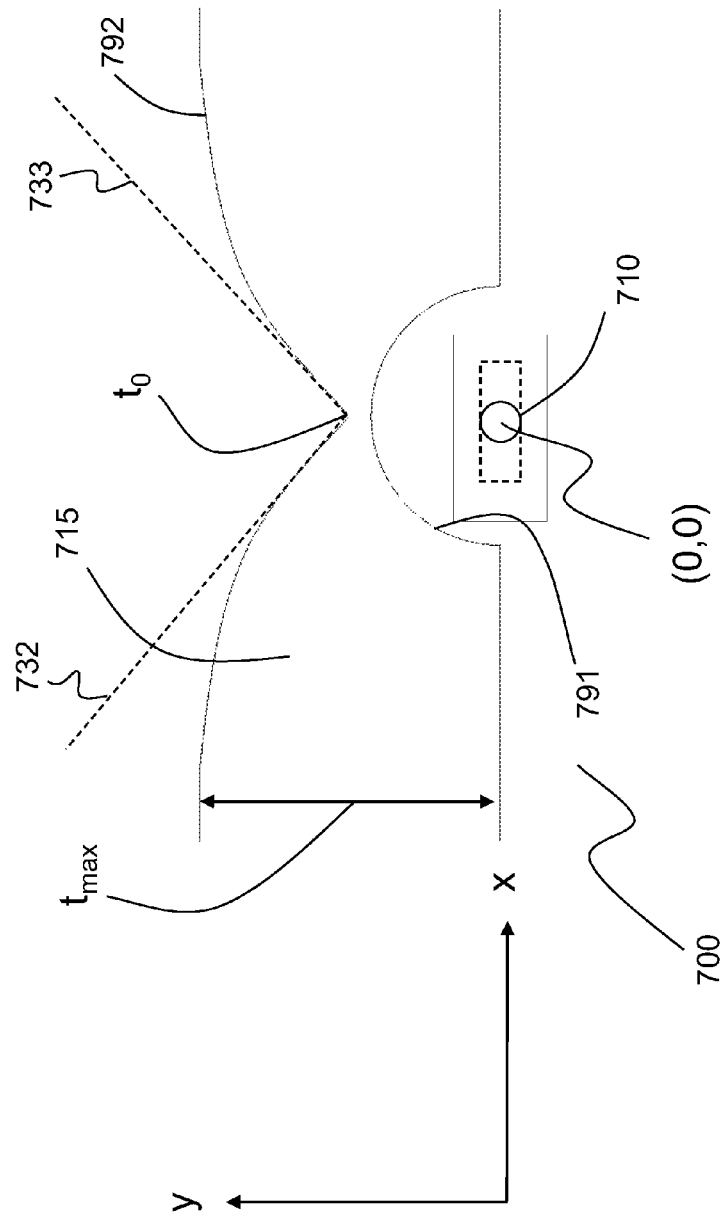
FIG. 7

FIG. 8

FIG. 9

FIG. 10
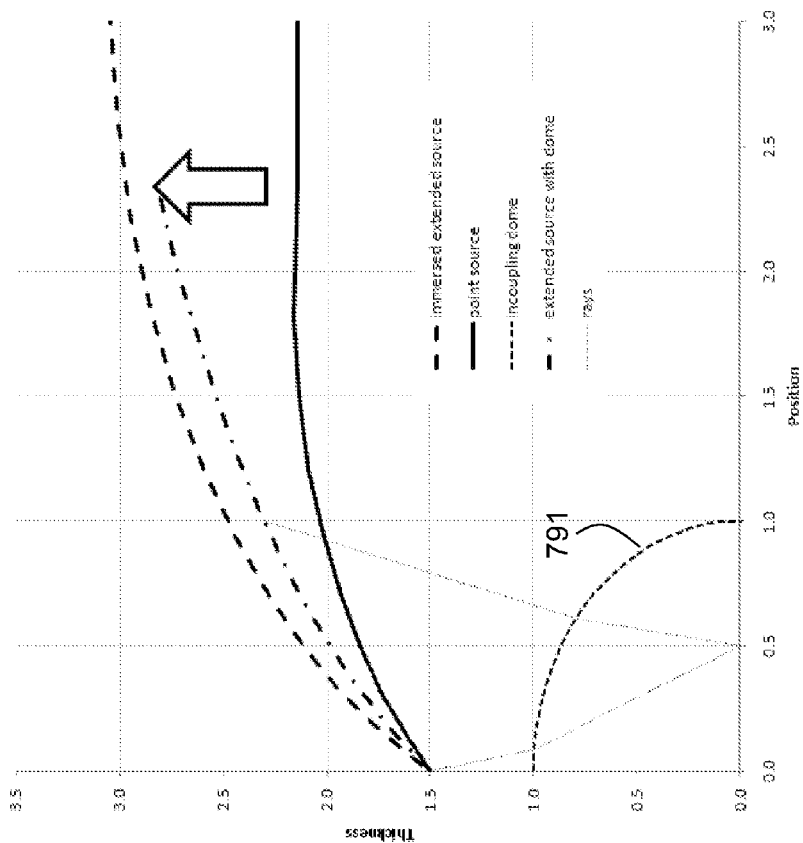
FIG. 11
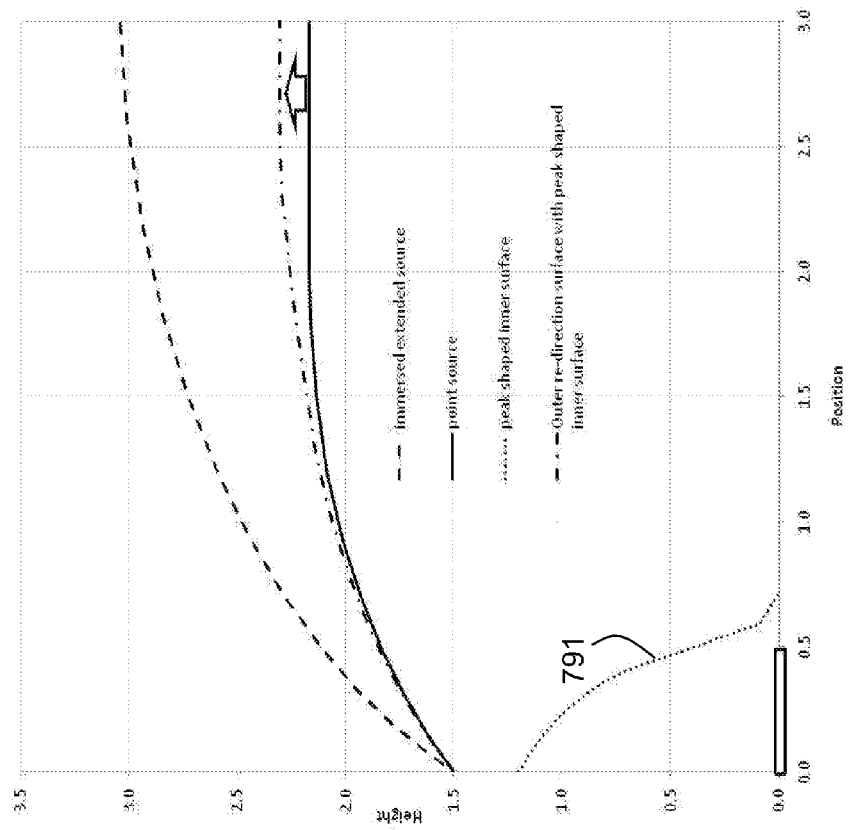
FIG. 12
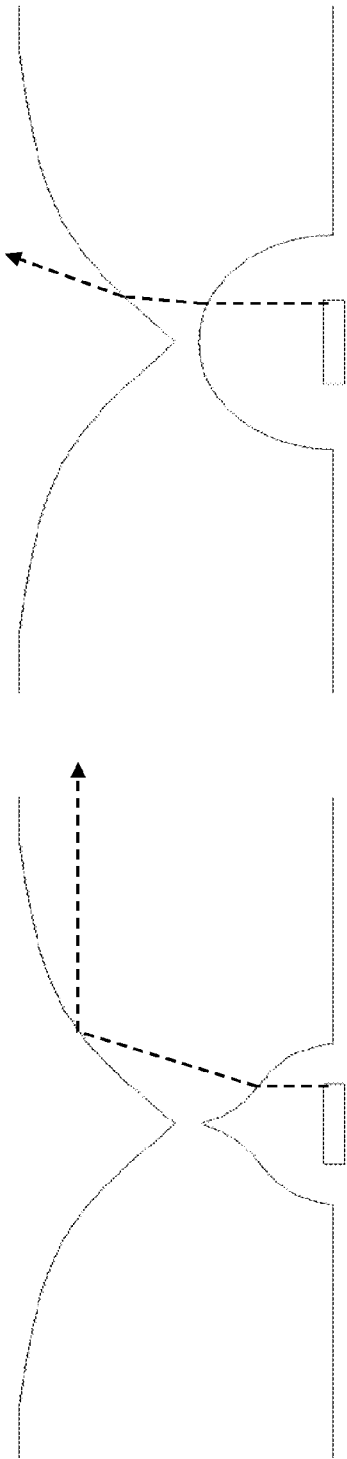
FIG. 13B

FIG. 13A

FIG. 13D

FIG. 13C

1400

1403

1492

1415

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1410

1412

1414
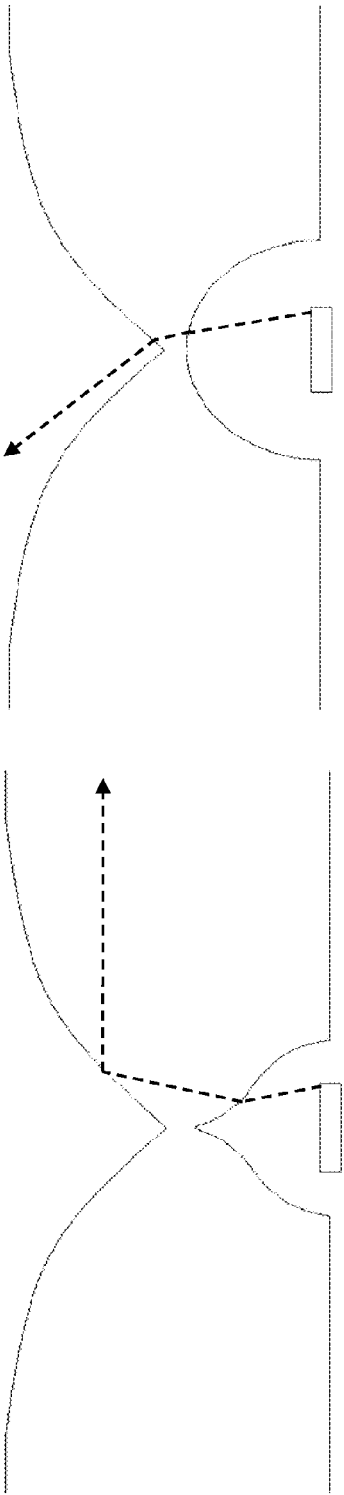
FIG. 14

FIG. 15

FIG. 16

TUBE LUMINESCENT RETROFIT USING LIGHT EMITTING DIODES

FIELD OF THE INVENTION

Embodiments of the present invention relate generally to the field of illumination systems, and, more specifically, to LED-based optical units.

DESCRIPTION OF THE RELATED ART

As the efficacy (measured in lumen per Watt) and the luminous flux (measured in lumen) of light emitting diodes (LEDs) increases and prices go down, it is expected that LED illumination and LED based lamps soon will be serious alternatives to and at a competitive level with until now predominant tube luminescent (TL) based lamps for providing large-area illumination. Such lamps are typically found in office buildings in forms of 15 centimeter- to 2.4 meter-long tubes, having diameters 5/8 inch, 1 inch, 1.25 inch or even larger, providing uniform luminance along the length of the tube. A typical TL luminous flux output density is 3000 lumen per meter tube length. For LED retrofit, also lower values may be found.

Current LED lamps are fabricated by placing a large number of LEDs in a linear array on a substrate where each LED is encompassed by a lens configured to re-direct light emitted by the LED in a direction perpendicular to the LED array and parallel to the plane of the substrate onto a curved reflection surface. FIG. 1 illustrates one such lamp 30 disclosed in US 2005/0265042. As shown, the lamp 30 includes two LED arrays, where each LED array comprises LEDs 10 disposed in a row on a substrate 20 along the length of the corresponding reflection surface 31. Because, as shown in FIG. 1, the reflection surface 31 is curved, the light incident thereon in a horizontal direction is reflected in the vertical direction, thereby providing illumination.

One drawback of such an arrangement is that providing a curved reflection surface poses fabrication challenges. Another drawback is that some of the light emitted by each of the LEDs is lost due to the light having to go through the corresponding lens, exit the lens, and then be reflected by the reflection surface.

What is needed in the art is a solution that can improve on at least some of the problems described above.

SUMMARY OF THE INVENTION

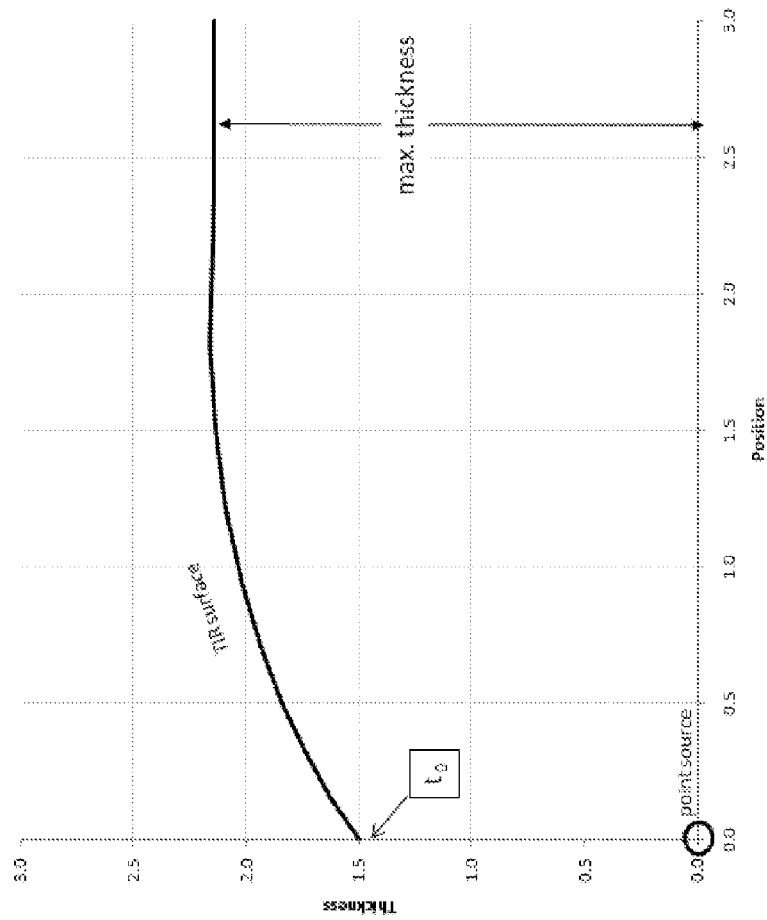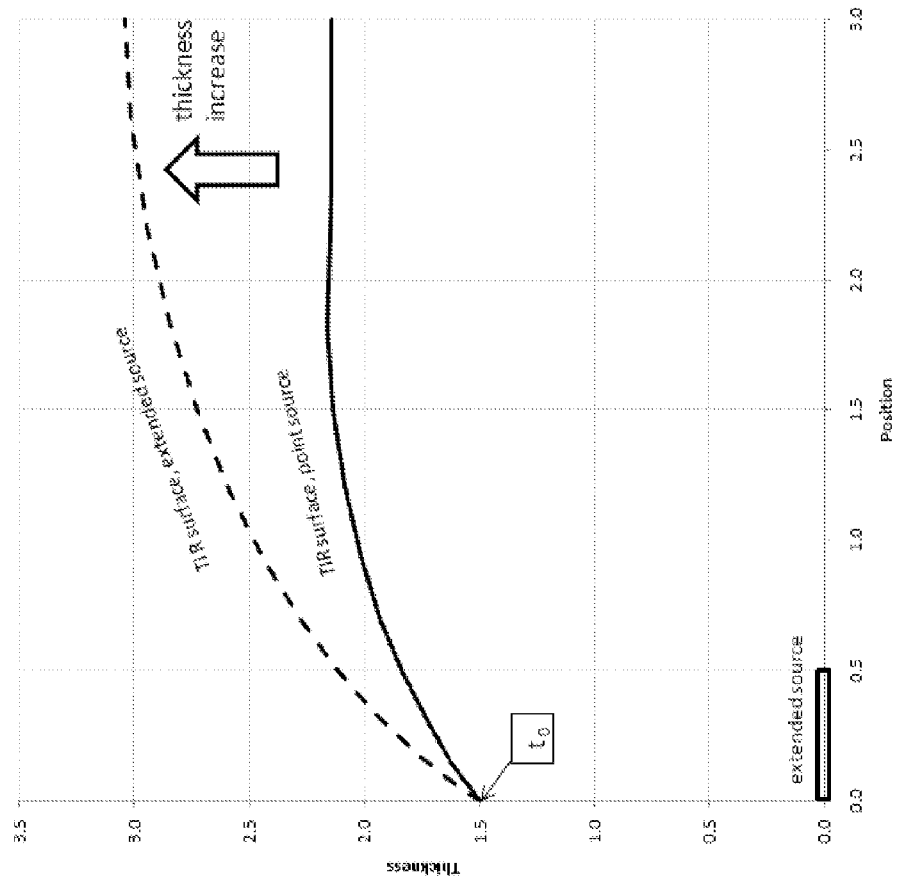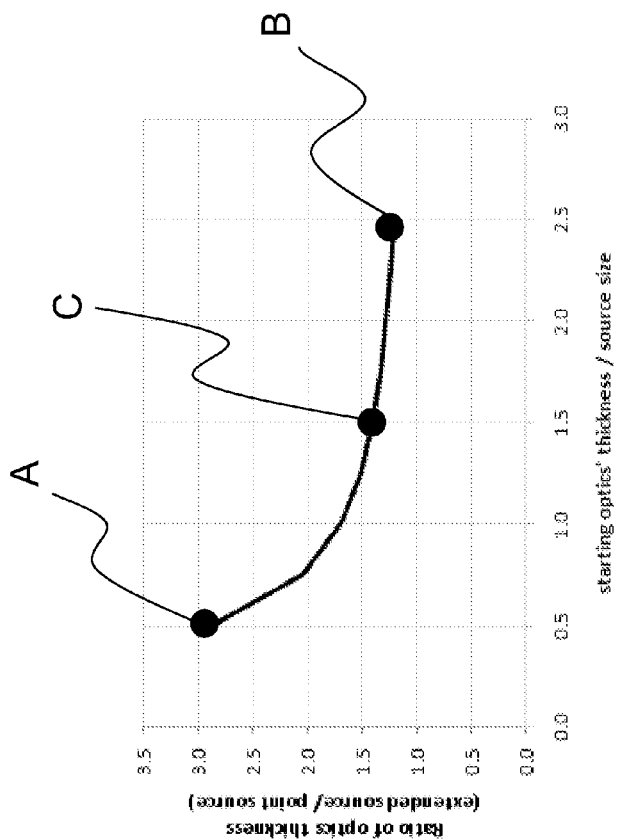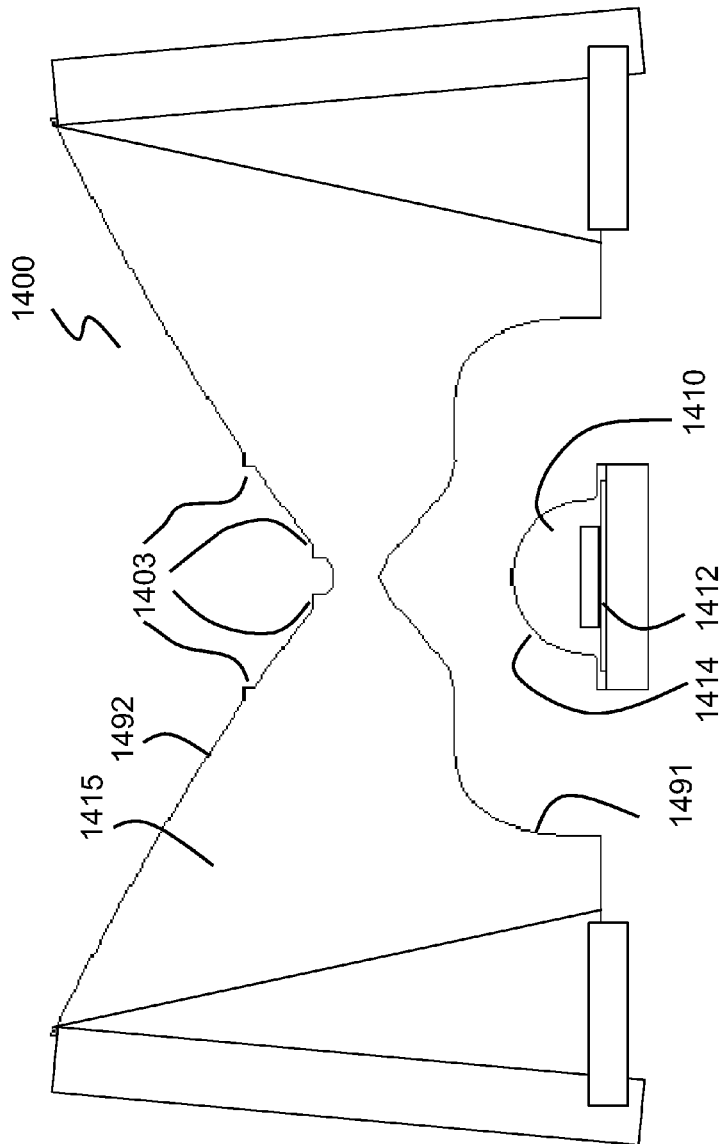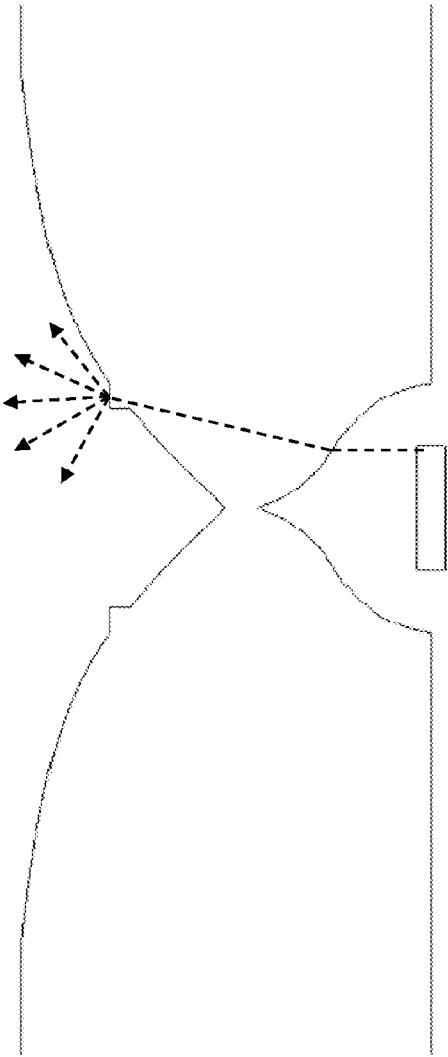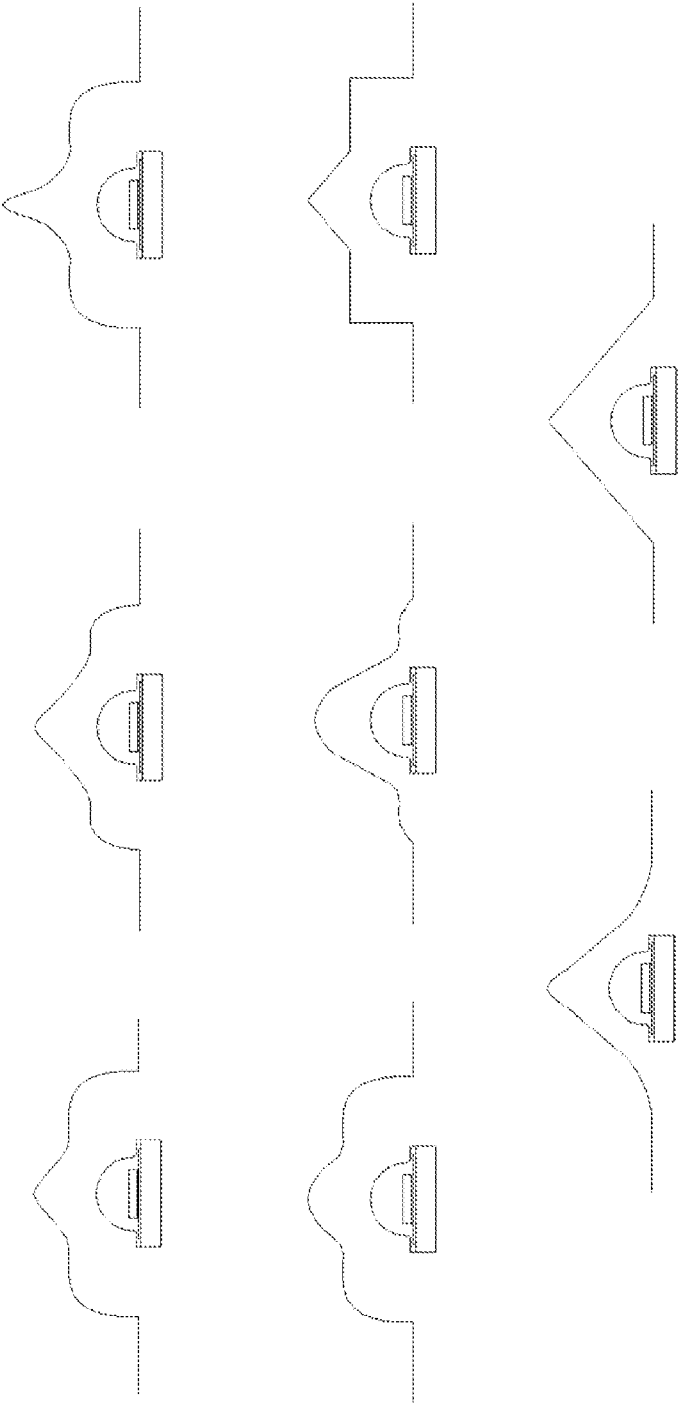According to one aspect of the invention, an optical unit is provided. The unit includes a LED disposed on a surface and a monolithic module encompassing the LED. The monolithic module includes a re-directing portion and a first diffusing portion, where the first diffusing portion is configured to diffuse light incident thereon and the re-directing portion is configured to re-direct at least a first portion of light emitted by the LED to be incident on the first diffusing portion.

According to another aspect of the invention, a lamp comprising two or more of such optical units is disclosed. In one embodiment, the two or more of such units may be arranged in a row within e.g. a tubular case, thereby together forming a linear light source. In another embodiment, a number of such units may be arranged in a grid or in any other pattern, thereby together forming an areal light source. The lamp may further include an optional cover which could e.g. provide additional diffusion of the light generated by the units.

According to yet another aspect of the invention, a lamp comprising at least two LEDs encompassed by a single monolithic module is disclosed ("extruded profile").

As used herein, the term "monolithic" is used to describe a module where a portion of the module having one functionality (e.g. the light diffusing portion) is an integral part of another portion of the module having another functionality (e.g. the light propagating portion) or, in other words, where the different optical properties are realized on different portions of one single body.

The present invention is based on the recognition that making the first diffusing portion an integral part of the re-directing portion of the monolithic module allows significantly simplifying the fabrication of the optical system while preserving the desired functionality. Providing the first diffusing portion may then simply comprise e.g. applying white paint to the appropriate surfaces of a lens or e.g. using 2K molding, where the lens could be employed to re-direct light emitted by the LED to be incident onto the white paint or plastic.

In an embodiment, the re-directing portion is further configured to guide a second portion of light emitted by the LED to not be incident on the first diffusing portion. This embodiment provides that some of the light emitted by the LED may "leak out" from the monolithic module without being diffusively reflected by the first diffusing portion. In one embodiment, such "leaked out" light could comprise 5-10% of the light emitted by the LED, however, this percentage may be further adjusted in order to e.g. obtain sufficiently uniform appearance of the lit unit. For maximal efficiency with highest glare reduction, this percentage should be as low as possible. However, for minimized spot-non-uniformity, the summed amounts of lumen per unit surface of the lamp from the leaked-out light and from the light diffused by the diffusing portion should preferably be the same everywhere on the observed surface.

Positions and shapes where the light leaks out (e.g., top center of the monolithic module, the corners of the module, etc.) and the amount and direction of the leaked light rays may also be optimized in terms of the uniform source luminance. For a purely refractive re-directing portion of the monolithic module, this can be done by adding carefully calculated corrugations (e.g. microstructures like micro-lenses, 'holographic diffuser'-like structures or other microstructures with a defined angular distribution) to selected positions of the outer surface of the module. If the outer surface of the module is a mirror, similar structures could be added but, in addition to that, the mirror can be locally made more or less transparent to get the desired kind of leakage. Alternatively or additionally, controlled light leakage may be achieved by introducing one or more concentric rings on the inner surface and/or the outer surface of the re-directing portion and/or extending between the inner surface and the outer surface. If the re-directing portion is rotationally symmetric, the center of the concentric rings may be adapted to coincide with an axis of symmetry of the re-directing portion. Such rings could allow easier modification of the optics. Therefore, the symmetry of the rings is preferably linked to the symmetry of the optics (i.e., the re-directing portion) and/or the lamp incorporating such optics rather than to the symmetry of the corresponding LED. Of course, in other embodiments, the rings could be made symmetric with respect to the axis of symmetry of the beam pattern of the corresponding LED.

Furthermore, there may be an extra volume diffuser and/or surface diffuser present between the optional diffusing cover and the module, to improve the uniformity of the provided illumination still further. The extra volume and/or surface diffuser may have an optimized shape and/or optical proper-

ties that vary over its volume or surface, respectively. If the re-directing portion of the module is transparent, it may also contain scattering elements in the bulk or on the surface to induce light leakage.

In an embodiment targeted for best spot uniformity, the second portion may include less than 45% of the light emitted by the LED. This embodiment advantageously specifies that most of the light emitted by the LED (55% or more) can be diffused.

In an embodiment targeted for best efficiency but not for best spot uniformity, the second portion may include less than 5-10% of the light emitted by the LED. This embodiment advantageously specifies that most of the light emitted by the LEDs (90% or more) can be diffused with only a small fraction of the light being "leaked out" from the module.

In an embodiment, the monolithic module may further include a second diffusing portion and the re-directing portion may further be configured to re-direct a third portion of light emitted by the LED to be incident on the second diffusing portion so that a projection (onto the 'back plane' surface where the LED is mounted on) of the average direction of the re-directed first portion of light and a projection (onto the 'back plane' surface where the LED is mounted on) of the average direction of the re-directed third portion of light form an angle between 0 degrees and 180 degrees. This embodiment specifies that some of the light emitted by the LED may be re-directed e.g. not only to the opposing side surfaces of the module, but also in other directions. This may be particularly advantageous for obtaining uniform illumination from lamps including e.g. four or more such units arranged in a rectangular pattern, all of the units thereby together forming an areal light source.

In an embodiment, the monolithic module may be rotationally symmetric with an axis of symmetry of the monolithic module coinciding with an axis of symmetry of a beam pattern of the LED.

As used herein, the term "rotationally symmetric structure" refers to a structure having symmetry with respect to rotations to certain or all angles around an axis of symmetry of the structure. In one embodiment, the monolithic module may be rotationally symmetric with respect to rotations of all angles around the axis of symmetry of the module, thus, having a circular top profile. In another embodiment, the monolithic module may be rotationally symmetric with respect to rotations of only particular angles around the axis of symmetry of the module, thus, having a non-circular but symmetric top profile. For example, a monolithic module which has rotational symmetry with respect to rotations of 90 degrees may have a square top profile.

Further, as used herein the term "beam pattern" of a LED refers to the intensity distribution of the LED which gives the flux per solid angle in all direction of space.

In an embodiment, the LED may include a light emitting die and a dome disposed over the light emitting die and configured to seal the die, where the monolithic module is disposed over the dome. This embodiment specifies that the monolithic module may be included as "secondary optics," where, as used herein, this term refers to optical elements not included within a LED package. By contrast, the term "primary optics" typically refers to elements included within a LED package such as a light emitting die, a dome disposed over the die and configured to protect the die, etc.

In an embodiment, the LED may include a light emitting die and the monolithic module may be disposed immediately over the die. In contrast to the previous embodiment, this embodiment provides that the monolithic module may be included as "primary optics" in a LED package.

In yet other embodiments, the LED may include a number of light emitting dies having either the dome(s) disposed over them or directly the monolithic module.

In an embodiment, the re-directing portion may be configured to re-direct light by total internal reflection. In contrast to some prior art implementations which re-direct light with mirrors, this embodiment provides the advantage of the re-directing portion having minimal losses in guiding the light emitted by the LED.

In an embodiment, the first diffusing portion includes a material having diffusive properties disposed on parts of the re-directing portion of the monolithic module. Such a material may e.g. be white paint or white plastic.

In an embodiment, the unit may further include a diffusing cover configured to diffusively transmit light incident thereon, where the first diffusing portion may be configured to diffusively reflect the light incident thereon to be incident on the diffusing cover. This embodiment provides for additional diffusion by a diffusively transmitting cover. In a preferred embodiment, each beam of the first portion of light emitted by the LED is diffusively reflected only once by the first diffusing portion before either being directly transmitted out of the unit or being diffusively transmitted out of the unit via the cover. The light being reflected in this manner allows keeping light losses to a minimum.

In an embodiment, the LED may comprise a high-power LED capable of emitting light with luminous flux of 65 or more lumens. Including high-power LEDs in lamps allows using less LEDs to obtain the desired luminance output from the lamps, thereby decreasing the cost and the complexity of the lamps. In addition, since high-power LED dies capable of emitting such fluxes usually have sizes larger than 1×1 mm^2, including a monolithic module where the inner surface of the module is modified to include a peak is particularly advantageous for such LEDs. However, while the embodiments disclosed herein may be especially beneficial for using high-power LEDs, of course, the teachings of the present invention could also be implemented with LEDs having luminous flux of less than 65 lumen.

In an embodiment, the monolithic module may comprise an inner surface and an outer surface such that the inner surface is adapted to form a chamber, where the chamber is adapted to at least partially encompass the LED, the inner surface is adapted to refract at least a first part of the first portion of light emitted by the LED to be incident on the outer surface (before being incident on the first diffusing portion), the outer surface is adapted to reflect the first part of the first portion of light incident thereon by total internal reflection, and the inner surface comprises a peak. The peak may be considered to be formed by two portions of the inner surface and would preferably be adapted to be above the center of the LED. In various embodiments, in a cross-sectional view of the unit, the cross-section being taken so as to include an axis of symmetry of the beam pattern of the LED, the two portions could comprise e.g. two linear portions of the inner surface joining at an angle (i.e., the two linear portions form an angle less than 180 degrees), two convex curves, two concave curves, or any combination of each of the two portions being a linear portion, a convex curve, or a concave curve, where, optionally, the peak may further be rounded. In some embodiments, the peak may be considered to be a "head" of the inner surface of the monolithic module while the portions of the inner surface next to the peak could be considered to be the "shoulders." However, in other embodiments, the peak may be considered to be a "head" of the inner surface without having any "shoulders" in the inner surface of the monolithic module.

As used herein, the inventive concept of an inner surface of a monolithic module comprising a peak is intended to cover all embodiments where the inner surface is adapted to form a chamber, around a LED, which chamber has aspherical, generally convex shape. The term "generally convex" is used to describe a shape that, while it may include some concave or linear portions, is, in general, convex, such as e.g. the inner surfaces shown in FIG. **16**. In line with these definitions, the concept of the inner surface comprising a peak does not cover the inner surface forming a dome-shaped chamber (because dome is spherical, not aspherical) and does not cover the inner surface forming a rectangular chamber with the LED adapted to be disposed along a side of the rectangle (because the rectangle is not "generally convex").

Such a monolithic module could be used to re-direct the light emitted by the LED from substantially vertical direction to substantially horizontal or downward horizontal ("backwards") direction. Such a module could also be used as an incoupling structure adapted to couple light emitted by the LED into a light guide, in which case the module could be an integral part of the light guide.

The idea of the inner surface of the monolithic module having a peak is based on the recognition that, when thickness of the module is reduced to the point that the size of the LED's emitting surface is comparable with the thickness of the module, the LED may no longer be considered to be a point light source emitting light from a single point at the center of the emitting surface. Instead, particular attention must be given to the extended size of the LED's emitting surface when determining the shape of the module that would allow all light beams emitted by the LED and incident on the outer surface to be reflected by TIR. When such attention is not given, light beams emitted from near the edges of the LED's emitting surface could enter the module at such an angle that a TIR condition at the outer surface of the module is not satisfied and these light beams will escape, or leak out from, the module. Therefore, care should be taken to ensure that light beams emitted from near the edges of the LED's emitting surface are incident on the outer surface of the module in a manner that the TIR condition would still be satisfied. Without increasing the overall thickness of the module, such care includes adapting the shape of the inner surface with respect to the maximum thickness of the module and the shape of the outer surface of the module so that all of the light beams emitted by the LED and incident on the inner surface, even the light beams emitted from near the edges of the LED's emitting surface, could be refracted by the inner surface at such angles that the angles of incidence of the refracted light beams on the outer surface of the LED would satisfy the TIR condition. Only then can substantially all of the light beams emitted by the LED be contained in the monolithic module.

A dome-shaped inner surface used in the prior art implementations, described below and illustrated in FIG. **5**, is not optimal in terms of the minimized light leakage because some of the light beams emitted from near the edges of the LED may leak out from the outer surface of the module, as shown in FIGS. **13**B and **13**D and explained in greater detail below. By contrast, an inner surface according to the embodiments of the present invention including a peak above the LED is more optimal because only for such not-dome-shaped surfaces a shape could be determined, with respect to the shape of the outer surface and the maximum thickness of the module, so that all of the light beams emitted by the LED would be refracted by the inner surface at such angles that the angles of incidence of the refracted light beams on the outer surface of the module would satisfy the TIR condition.

In an embodiment, not the entire monolithic module but only the inner surface of the module may be rotationally symmetric with an axis of symmetry of the inner surface adapted to coincide with an axis of symmetry of a beam pattern of the LED (i.e., the chamber adapted to encompass the LED may be made rotationally symmetric) and vice versa.

In an embodiment, in a cross-section of the unit, the cross-section including the axis of symmetry of the beam pattern of the LED, the peak is at a point along the axis of symmetry of the beam pattern of the LED. Thus, the inner surface of the module would include a single peak above the LED, along the axis of symmetry of the beam pattern of the LED.

Hereinafter, an embodiment of the invention will be described in further detail. It should be appreciated, however, that this embodiment may not be construed as limiting the scope of protection for the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

In all figures, the dimensions as sketched are for illustration only and do not reflect the true dimensions or ratios. All figures are schematic and not to scale. In particular the thicknesses are exaggerated in relation to the other dimensions. In addition, details such as LED chip, wires, substrate, housing, etc. have sometimes been omitted from the drawings for clarity.

FIG. **1** illustrates a LED-based lamp according to prior art;

FIG. **2**A illustrates a three-dimensional view of an optical unit, according to one embodiment of the present invention;

FIG. **2**B illustrates a three-dimensional view of an optical unit, according to another embodiment of the present invention;

FIG. **2**C illustrates a cross-sectional side view of the optical units of FIGS. **2**A and **2**B;

FIG. **3**A illustrates a three-dimensional view of an optical unit, according to yet another embodiment of the present invention;

FIG. **3**B illustrates a cross-sectional side view of the optical unit of FIG. **3**A;

FIGS. **4**A-**4**E illustrate some exemplary ways for arranging the optical units of FIGS. **2**A, **2**B, and **3**A within a lamp, according to various embodiments of the present invention;

FIG. **4**F illustrates an example of arranging the optical units of FIG. **3**A within a lamp while employing a single monolithic module encompassing all of the LEDs, according to one embodiment of the present invention;

FIG. **4**G illustrates a three-dimensional view of the arrangement of FIG. **4**F;

FIG. **5** illustrates a light guide according to prior art;

FIG. **6**A illustrates a three-dimensional view of an optical unit with an optimized inner surface of a monolithic module encompassing a LED, according to an embodiment of the present invention;

FIG. **6**B illustrates a cross-sectional side view of the optical unit of FIG. **6**A, according to one embodiment of the present invention;

FIG. **7** provides a schematic illustration of an optical unit used in the description of FIGS. **8**-**12**;

FIG. **8** provides a computation result for a cross-sectional shape of the outer surface of a re-directing structure satisfying the TIR condition when the LED is considered to be a point source emitter;

FIG. **9** provides a computation result for a cross-sectional shape of the outer surface of a re-directing structure satisfying the TIR condition when the LED is considered to be an immersed extended source emitter;

FIG. **10** illustrates dependence of the optics size on the size of the emitting surface of the LED for the above-described re-direction structures satisfying the TIR condition;

FIG. **11** provides a comparison of the computation results for a cross-sectional shape of the outer surface of a re-directing structure satisfying the TIR condition when the LED is considered to be a point source emitter, or an immersed extended source or an extended source encompassed by a dome-shaped inner surface of the re-directing structure;

FIG. **12** provides a comparison of the computation results for the different cross-sections of the minimum thickness TIR re-directing structures with different incoupling chambers;

FIGS. **13A-13D** illustrate differences with respect to light leakage between a re-directing structure forming a dome chamber around a LED and a re-directing structure according to an embodiment of the present invention forming a chamber having a sharp peak above the LED;

FIG. **14** illustrates a cross-sectional side view in the plane **650** of an optical unit with controlled light leakage, according to one embodiment of the present invention;

FIG. **15** illustrates a cross-sectional side view in the plane **650** of an optical unit with controlled light leakage, according to another embodiment of the present invention; and

FIG. **16** illustrates inner surfaces comprising peaks of different shapes, according to various embodiments of the present invention.

DETAILED DESCRIPTION

In the following description, numerous specific details are set forth to provide a more thorough understanding of the present invention. However, it will be apparent to one of skill in the art that the present invention may be practiced without one or more of these specific details. In other instances, well-known features have not been described in order to avoid obscuring the present invention.

FIG. **2A** illustrates a three-dimensional view of an optical unit **200A**, according to one embodiment of the present invention. As shown, the unit **200A** includes a LED **210** encompassed by a module **215A** and disposed on the same plane (e.g., the top surface of a printed circuit board) as a bottom surface **205** of the module **215A**. Side surfaces **220A** of the module **215A** are made so that they diffusively reflect light incident on them. The bulk of the module **215A** is a re-directing and light propagating structure configured to guide the light emitted by the LED **210** to be incident onto the side surfaces **220A**.

Since portion of the module **215A** configured to diffusively reflect light is the side surface(s) of the module **215A** while portion of the module **215A** configured to guide light onto the diffusing portion is the bulk of the module **215A**, such a module **215A** may be said to be a monolithic module including a light diffusing portion (i.e., the surfaces **220A**) and a light re-directing portion (i.e., the bulk of the module **215A** and the rest of the surfaces of the module **215A** besides the surfaces **220A**), where the diffusing portion and the re-directing portion are integral portions of a single body. A person skilled in the art would recognize that since "diffusing of light" is also "re-directing of light," the diffusing portion also re-directs light incident thereon. However, for the discussions provided herein, the difference between the diffusing portion and the re-directing portion is that while the diffusing portion not only diffuses but also re-directs light, the re-directing portion re-directs but does not diffuse light.

In the embodiment shown in FIG. **2A**, the re-directing portion of the module **215A** may be a lens designed to change the path of light emitted by the LED **210** to be incident on the

diffusing surfaces **220A** mainly along the transverse direction (shown with arrows **242** and **244**) of the unit **200A** or of a lamp in which the unit **200A** could be incorporated.

In other embodiments, the module **215A** may have different shapes in order to guide light emitted by the LED **210** in other directions e.g. perpendicularly to the transverse direction as to allow mixing of light between different modules when placed next to each other. Furthermore, the surface and/or the side walls of the module **215A** may be optimized to redirect the light to provide the desired luminance over the whole length of the diffusing surfaces. One such embodiment is shown in FIG. **2B**, which illustrates a three-dimensional view of an optical unit **200B** according to another embodiment of the present invention. In FIG. **2B**, elements with the same reference numbers as in FIG. **2A** illustrate the same elements as in the FIG. **2A**. Therefore, all of the above discussions with respect to these elements are also appropriate here and, in the interests of brevity, are not repeated.

The unit **200B** differs from the unit **200A** in that the module **215B** is circularly symmetric with respect to all angles of rotation around an axis **255**, where the axis **255** is the axis of symmetry of a beam pattern of the LED **210**. The unit **200B** further differs from the unit **200A** in that the diffusing portion of the module **215B** is the surface shown as surface **220B** and that the bulk of the module **215B** is configured to guide the light emitted by the LED **210** onto the surface **220B** surrounding the LED **210** on all the sides, as opposed to guiding the light mostly onto the side surfaces **220A**.

As shown in the three-dimensional views of FIGS. **2A** and **2B**, both of the modules **215A** and **215B** may be symmetrical with respect to a plane shown as a plane **250**. In order to explain the operation of the units **200A** and **200B** in greater details, a cross-sectional side view of these units is illustrated in FIG. **2C**. The cross-section of FIG. **2C** is taken along the plane **250**, so that the cross-section of the unit **200A** looks the same as the cross-section of the unit **200B**. Therefore, in FIG. **2C**, element numbers listed with a dash sign (e.g. "**215A/ 215B**") intend to indicate that the element could belong to the unit **200A** or to the unit **200B** and the following description applies to both units.

In operation, the LED **210** emits light (either as a top-emitter LED or a side-emitter LED) which is incident on the module **215A**. In various embodiments, the LED **210** may comprise a high-power LED, capable of providing light with luminous output of 65 or more lumen. As shown in FIG. **2C**, the LED **210** may include a LED die **212** covered with a dome **214**. The LED die **212** is configured to emit light in response to a drive signal. Material used as the LED die **212** primarily determines characteristics of the LED **210**, such as e.g. color, brightness, and/or intensity of light. Possible materials that could be used for the LED die **212** include inorganic semiconductors, such as e.g. GaN, InGaN, GaAs, AlGaAs, or organic semiconductors, such as e.g. small-molecule semiconductors based on Alq_3 or polymer semiconductors based e.g. on the derivatives of poly(p-phenylene vinylene) and polyfluorene.

The dome **214** is usually configured to protect the LED die **212** from the environmental factors and/or determine characteristics of the LED such as e.g. maximizing the total luminous flux of the LED while still fitting within a certain envelope or matching the intensity profile of the LED for the largest number of applications. In various embodiments, the dome **214** may actually have a different shape than the half-dome illustrated in FIG. **2C**, suitable for particular requirements for applications of the LED **210**.

As shown in FIG. **2C** with a gap **235**, in the illustrated embodiment, the module **215A** encompasses the LED **210**

without being in physical contact with the LED **210**. Thus, the gap **235** is the gap between the dome **214** of the LED **210** and the module **215**A. The gap **235** may be air or may be filled with a material having suitable optical properties. In the latter case, this may require a different shape of the module **215**A. In an alternative embodiment (not shown in FIG. **2**C), the module **215**A may also be in physical contact with the LED **210**.

While FIG. **2**C illustrates the LED **210** including the light emitting die **212** covered with the dome **214**, the unit **200**A could also be implemented without including the dome **214** as a part of the LED **210**. Instead, the module **215**A itself may be used to perform the functions of the dome over the light emitting die **212**. In such embodiments, the module **215**A may be referred to as a "primary" optical component of a LED package including the LED **210** and the module **215**A and may be disposed either immediately over the light emitting die **212** (i.e., be in contact with the die, no gap between the LED **210** and the module **215**A, such as e.g. the gap **235**) or may encompass the die **212** with a gap (similar to e.g. the gap **235**).

As shown in FIG. **2**C, in operation, the LED die **212** emits light, schematically shown with rays **251** and **252**, which is first incident on the module **215**A. The re-directing portion of the module **215**A is then configured to refract and reflect the majority of the light (e.g. greater than 80-90%) to be incident onto the diffusing surfaces **220**A. FIG. **2**C illustrates the ray **251** to be incident on the surface **220**A at a point **261** and the ray **252** to be incident on the surface **220**A at a point **262**. In turn, the surfaces **220**A diffusively reflect the light incident on them in different vertical directions, as is schematically shown with arrows originating from the points **261** and **262**.

Such operation may be illustrated by tracing, for example, the ray **252**. The ray **252** has three segments: **252***a*, **252***b*, and **252***c*.

The segment **252***a* illustrates a segment of the ray **252** emitted by the LED die **212** before it is refracted at the boundary between the material filling the gap **235** and the module **215**A. Note that, while this is not illustrated in FIG. **2**C in order not to clutter the drawings, the segment **252***a* may also be refracted at the boundary between the dome **214** and the material filling the gap **235**, depending on the refractive indices of the respective materials at the boundary.

The segment **252***b* illustrates a segment of the ray **252** after it was refracted at the boundary between the material filling the gap **235** and the module **215**A and being guided by the re-directing portion of the module **215**A to be incident on the surface **220**A at the point **262**.

In a preferred embodiment, the re-directing portion of the module **215**A may be fabricated from a material that does not absorb light emitted by the LED **210** and is designed to guide the light emitted by the LED **210** based on the total internal reflection principle. For example, the re-directing portion of the module **215**A may be fabricated from transparent PMMA, polycarbonate, glass, or comparable materials. In other embodiments, the re-directing portion of the module **215**A could also be implemented with mirror surfaces (e.g. metallic or dielectric), either hollow or filled with transparent material.

The segment **252***c* illustrates a part of the ray **252** after it was diffusively reflected by the surface **220**A. In one embodiment, the surface **220**A may comprise a flat white material disposed on the surface of the module **215**A and comprised e.g. of white plastic, white paint or the like.

While FIG. **2**C illustrates rays to be guided onto the surface **220**A on the right side of the unit **200**A, similar illustrations and descriptions could be extended to the surface **220**A on the other sides of the unit **200**A.

The module **215**A being a monolithic module comprising a diffusing portion and a re-directing portion is in contrast to prior art implementations where the light emitted by a LED was re-directed by a lens onto a diffuser which was a different element, such as e.g. a separate curved surface illustrated in FIG. **1**. Fabricating a unit where the diffusing portion is an integral part of the re-directing structure by e.g. applying white paint to the appropriate portions of the re-directing structure or e.g. using a 2K-molding process could make fabrication of the fixtures, systems, and/or lamps with units such as **200**A significantly easier in comparison with the structure of FIG. **1**. In addition, to minimize optical losses, the bottom surface **205** and/or the relevant (i.e., close to the LED) part of the mounting plane on which the monolithic unit and the LED are mounted may be converted into a reflecting diffusing surface, by also applying white paint or 2K mould-ing to these parts. This may reduce the optical requirements on the other surfaces of the lamp, so that the requirements may then be optimized for e.g. best mechanical or thermal properties. This advantage of reduced requirements is further enhanced if the monolithic module is implemented as the round shape **215**B, or if it is implemented as shape **215**A but with three, four, or more diffusively reflecting surfaces **220**A, so that the top surface and the bottom surface of the module **215**A each have the shape of a polygon.

In order to minimize light losses, the module **215**A may be designed in such a way that the light is preferably only reflected once by the diffusing surface **220**A before escaping the unit **200**A or before being incident on an optional cover covering the unit **200**A (not shown). In order to approach this optimum as much as possible, the re-directing portion of the module **215**A could have a beam pattern of which the largest possible fraction hits the diffusing portion of the module **215**A. In one embodiment, the optional cover may comprise a transparent material so that the cover simply transmits the light incident thereon. Alternatively, the optional cover may comprise a diffusively transmitting layer, configured to dif-fusively transmit the light incident thereon, thereby improv-ing the uniformity of the illumination provided by the unit **200**A.

As used herein, the term "diffusively reflect" and the derivatives thereof refer to more than 80-90% of light being quasi-Lambertian reflected and the term "diffusively trans-mit" and the derivatives thereof refer to more than 40-60% of light being quasi-Lambertian transmitted. Preferably, the dif-fusive properties of the optional cover should be optimized to maximize the amount of transmitted light while still fulfilling the uniformity requirements.

The re-directing portion of the module **215**A may be designed to guide most of the light generated by the LED **210** to be incident on the surface **220**A. Optionally, at least a portion of the bottom of the module **215**A may be made at least partially reflective in order to prevent absorption of light which would lower efficiency of the unit **200**A.

The optimal fraction of the light generated by the LED **210** to be incident on the surface **220**A depends on the acceptable compromise between luminance uniformity and efficiency for a particular device where the unit **200**A would be employed. For example, for a lamp including two or more units **200**A arranged e.g. in a row, 100% of the light generated by each of the LEDs **210** could be incident on the respective surfaces **220**A for best efficiency with highest glare reduc-tion.

In other embodiments, the re-directing portion of the mod-ule **215**A may include one or more segments (not illustrated in FIG. **2**C) from which a portion of light emitted by the LED **210** may "leak out" (i.e., escape the module **215**A without

being guided to be incident on the surface **220A**). In one further embodiment, the leaked out light may be incident on an optional diffusing cover that could cover the module **215A** (not shown in FIG. **2C**). Such an optional diffusing cover may be configured to diffusively transmit light incident thereon (similar to the optional diffusing cover described above).

While the above description of FIG. **2C** refers to the elements of the unit **200A**, similar teachings with minor modifications that would be apparent to a person skilled in the art may be applicable to the unit **200B**. The module **215B** is rotationally symmetric with respect to rotations of all angles around the axis **255**. Therefore, any cross-section of the unit **200B** taken along any arbitrary plane that includes the axis **255** would look like the cross-section taken along the plane **250** shown in FIG. **2C**. For each of these cross-sections, similar reasoning may be applied in analyzing how the light emitted by the LED **210** is guided in the module **215B**. Such an embodiment could be particularly beneficial for areal lamps having a number of the units **200B**, where e.g. 4 or 9 units **200B** could be arranged in a square grid to act together as an areal light source or e.g. 6 units **200B** could be arranged in a triangular grid to also act together as an areal light source, as shown in FIGS. **4D-4E** and described in greater detail below.

FIG. **3A** illustrates a three-dimensional view of an optical unit **300**, according to yet another embodiment of the present invention, and FIG. **3B** illustrates a cross-sectional side view of the optical unit **300**. As shown in FIGS. **3A** and **3B**, the unit **300** includes a LED **310** and a module **315** having diffusively reflecting surfaces **320**. The LED **310** may be analogous to the LED **210**, described above. Therefore, all of the discussions above with respect to the LED **210** are applicable here for the LED **310** and, in the interest of brevity, are not repeated here.

The unit **300** and the module **315** are similar to the unit **200A** and the module **215A**, respectively, therefore all of the discussions above with respect to the unit **200A** and the module **215A** are applicable here for the unit **300** and the module **315**, respectively, but there are also some differences.

One difference is that the shape of the module **315** is particularly beneficial for making linear light sources by placing a number of LEDs **310** in a row and having a single module **315** encompassing all of the LEDs **310**, forming a so-called "extruded" profile as shown in FIGS. **4F** and **4G** with a lamp **400F**, described below. Again, manufacturability may be significantly simplified and made less expensive by using an extruded profile. Note that the white diffusing side surfaces can be coextruded allowing to fabricate the optics in one continuous process. Furthermore, the optional diffusing cover could also be coextruded in the same process.

Two or more units **200A**, **200B**, and/or **300** described above may be employed in a lamp for e.g. providing large area illumination. FIGS. **4A** and **4B** illustrate some exemplary ways for arranging the optical units such as units **200A** and **300** within a lamp, FIGS. **4C-4E** illustrate some exemplary ways for arranging the optical units **200B** within a lamp, and FIGS. **4F** and **4G** illustrate different views of an example of arranging the units **300** in a lamp, according to various embodiments of the present invention.

FIGS. **4A-4E** provide the top view of lamps **400A-400E**, respectively. As can be seen from FIGS. **2A-2C**, **3A** and **3B**, the top profiles of the units **200A**, **200B**, and **300** coincide with the top profiles of the monolithic modules **215A**, **215B**, and **315**, respectively, included therein. Therefore in FIGS. **4A-4E** the monolithic modules **215A**, **215B**, and **315** are not identified specifically but the striped portions of the units **200A**, **200B**, and **300** are intended to illustrate the diffusing portions of the monolithic modules included therein.

FIG. **4A** illustrates that four optical units such as the unit **200A** or the unit **300** may be disposed in a row on a substrate **405A** where, for each of the units, the diffusing portions are located in a transverse direction of the lamp **400A**. Described differently, FIG. **4A** illustrates that the long axis of each of the diffusing portions is parallel to the longitudinal direction of the lamp **400A**. The units **200A** or **300** arranged in this manner may together act as a linear light source. Based on symmetry considerations, the maximum luminance on the white surfaces will be in the plane **250** in FIG. **2A**. As the diffusers are aligned in two uninterrupted rows, and have neighboring short sides, the configuration of FIG. **4A** will more or less show the appearance of two parallel lines. Arranging the units in a line allows leakage of the light from one unit to the next, which could help evening out any color/flux difference between neighboring LEDs.

FIG. **4B** illustrates that four optical units such as the unit **200A** or the unit **300** may be disposed in a row on a substrate **405B** where, for each of the units, the diffusing portions are located in a longitudinal direction of the lamp **400B**. Described differently, FIG. **4B** illustrates that the short axis of each of the diffusing portions is parallel to the longitudinal direction of the lamp **400B**. The units **200A** or **300** arranged in this manner may also together act as a linear light source. Based on symmetry considerations, the maximum luminance on the white surfaces would be in the plane **250** in FIG. **2A**. When the diffusively reflecting surfaces would be aligned in one interrupted row with neighboring long sides, the configuration of FIG. **4B** would more or less show the appearance of one line. In terms of luminance distribution, the linear direction of the line source is accentuated in such an arrangement. On the other hand, such an arrangement could also allow, if addressed individually, to switch clearly defined pixels on and off.

FIG. **4C** illustrates that four optical units **200B** may be disposed in a row on a substrate **405C** where, for each of the units, the re-directing portion of the monolithic module is configured to guide the light emitted by the corresponding LED in all directions around the LED. The units **200B** arranged in this manner may also together act as a linear light source.

FIG. **4D** illustrates that nine optical units **200B** may be disposed in a square grid on a substrate **405D** where, for each of the units the re-directing portion of the monolithic module is configured to guide the light emitted by the corresponding LED in all directions around the LED. The units **200B** arranged in this manner may together act as an areal light source.

FIG. **4E** illustrates that six optical units **200B** may be disposed in a triangular grid on a substrate **405E** where, for each of the units the re-directing portion of the monolithic module is configured to guide the light emitted by the corresponding LED in all directions around the LED. The units **200B** arranged in this manner may also act together as an areal light source.

Finally, FIG. **4F** illustrates that the units **300** may be arranged in a row in a lamp **400F** while employing a single module **315** encompassing all of the LEDs **310** of all of the units **300** (i.e., the extruded profile). FIG. **4G** illustrates a three-dimensional view of such an arrangement. As described above, implementing an extruded profile may allow simplifying manufacturability and decreasing the overall cost of the lamp by co-extruding all of the diffusing side surfaces and an optional diffusing cover in a single continuous process.

FIGS. **4A-4G** are intended to provide some schematic illustrative embodiments and persons skilled in the art will recognize that there could be many various other ways for

arranging the units **200A**, **200B**, and/or **300** in a lamp. For example, the diffusing portions within the lamps **400A** and **400B** illustrated in FIGS. **4A** and **4B**, respectively, do not have to have a long axis and a short axis because, in other embodiments, such diffusing portions could also be square. TIR Optics with Optimized Incoupling Structure

The optical units described above employ monolithic modules to re-direct at least a part of the light beams emitted by a LED in a substantially vertical direction to propagate in a substantially horizontal downwards or horizontal direction by reflecting the light beams incident on the outer surface of the modules by TIR. As used herein, the term "inner surface" of a monolithic module refers to surfaces **291** and **391** illustrated in FIGS. **2C** and **3B**, respectively, while the term "outer surface" of a monolithic module refers to surfaces **292** and **392** illustrated in FIGS. **2C** and **3B**, respectively.

EP 0 945 673 A1 discloses a TIR-based light guide, illustrated in FIG. **5**, for guiding the light beams emitted by a top-emitting LED in a substantially vertical direction to propagate in a horizontal and/or horizontal downwards direction. As shown in FIG. **5**, a light guide **520** having a through hole **550** of an inverted triangular shape above a top-emitting LED **530** is disposed on a substrate **540**. As shown in FIG. **5**, the light guide **520** has a dome-shaped inner surface **570** surrounding the LED **530**, a top surface **510**, and a pair of opposite reflecting surfaces **580** radially extending from the inner surface **570** to form a radial reflection surface, where sides **550A** of the through hole **550** are used to re-direct, by TIR, the light emitted by the LED in a longitudinal direction of the light guide.

One problem with the light guide illustrated in FIG. **5** is that the resulting structure is relatively thick, which is undesirable for applications requiring thin building height or applications where the incoupling structure is part of the light guide and where, therefore, the thickness should be limited for manufacturability reasons. In addition, no attention seems to be given to the extended size of LED's emitting surface, which, as explained below, may lead to uncontrolled light leakage from the light guide. Yet another problem is that complexity is added by the shown symmetry where additional side mirrors are required to couple light into the light guide.

Described below is an approach that helps improving on at least some of these problems by modifying the shape of an inner surface of a monolithic module encompassing a LED. Embodiments described above are particularly advantageous for top-emitting LEDs. FIG. **6A** illustrates a cross-sectional side view of an optical unit **600** with a modified inner surface of a monolithic module **615**, according to an embodiment of the present invention. The cross-section is taken in a symmetry plane of the optical unit **600** similar to the plane **250** of the optical units **200A** and **200B** shown in FIGS. **2A** and **2B**. Thus, the cross-sectional side view shown in FIG. **6A** is similar to the cross-sectional side view shown in FIG. **2C**.

In one embodiment, similar to the optical units **200A/200B** and the optical unit **300**, the optical unit **600** may be used in the lamps **400A-400F** described above. In other embodiments, the module **615** can be part of a light guide, where the module would serve to couple all of the light emitted by the LED into a longer piece of transparent material guiding the light further away from the LED position, as schematically shown on FIG. **6B**.

As shown in FIG. **6A**, the optical unit **600** includes a LED **610** comprising a LED die **612** and a dome **614**, and the monolithic module **615**. The LED **610**, the LED die **612**, and the dome **614** may be analogous to the LED **210**, the LED die **212**, and the dome **214**, respectively, described above. Therefore, all of the discussions above with respect to these ele-

ments are applicable here and, in the interest of brevity, are not repeated here. The module **615** also includes diffusively reflecting side surfaces **620** similar to the side surfaces **220A** illustrated and described in FIGS. **2A** and **2C**, and therefore, all of the discussions above with respect to the diffusing side surfaces are applicable here and will not be repeated.

The module **615** comprising a body having an inner surface **691** and an outer surface **692**, the inner surface **691** forming a chamber around the LED **610** is similar to the **215A**, therefore all of the discussions above with respect to the module **215A** are applicable here, but there are also some differences.

One difference is that, the inner surface **691** has a sharp peak **638** above the LED **610**. Angle **639** illustrates an opening angle of the peak **638**, described in greater detail below.

As shown in FIG. **6A** with a chamber **635**, in the illustrated embodiment, the inner surface **691** of the module **615** encompasses the LED **610** without being in physical contact with the LED **610**. Thus, the chamber **635** is the space enclosed between the dome **614** (or the die **612**, if the dome **614** is absent and the module **615** acts as "primary optics" being a part of the LED package) of the LED **610** and the module **615**. Similar to the gap **235** described above, in various embodiments, the chamber **635** may be filled with air or with a material having suitable optical properties. In the latter case, this may require a different shape of the module **615**.

In operation, the LED die **612** emits light in a substantially vertical direction (i.e., upwards) which is intended to be redirected by the re-directing portion of the module **615** in a substantially horizontal and/or horizontal downwards (or backwards) direction. As used herein, the term "horizontal downwards" is used to describe the direction towards the place on which the LED die is disposed. The re-direction may be illustrated by tracing one of the light beams emitted by the LED die **612**, a ray **651**, shown in FIG. **6A**.

As shown, the ray **651** includes three segments: **651**a, **651**b, and **651**c. The segment **651**a illustrates a segment of the ray **651** emitted by the LED die **612** before it is refracted at the boundary between the material filling the chamber **635** and the inner surface **691**. Note that, while this is not illustrated in FIG. **6A** in order not to clutter the drawing, the segment **651**a may also be refracted at the boundary between the dome **614** and the material filling the chamber **635**, depending on the refractive indices of the respective materials at the boundary. The segment **651**b illustrates a segment of the ray **651** refracted at the boundary between the material filling the chamber **635** and the inner surface **691** and being incident on the outer surface **692**. Finally, the segment **651**c illustrates that the ray **651** is being reflected at the outer surface **692** by TIR, thus re-directing the ray **651** from propagating in a substantially vertical direction to propagate in a substantially horizontal or backward direction.

Shaping the inner surface **691** to include the peak **638** allows operation of the optical unit **600** where all of the light beams emitted by the LED die **612** that are incident on the outer surface **692** after having been refracted at the inner surface **691** may be reflected at the outer surface **692** by TIR. The resulting structure is advantageous in comparison with the structure illustrated in FIG. **5** because uncontrollable light leakage from the module **615** is significantly reduced while the overall thickness of the structure is minimized since there is no need to include holes in the module that re-direct the light, as was done in the structure of FIG. **5** and since there is no need to increase the thickness of the module **615** to the point that the LED can be considered to be a point source emitter.

The advantages of having an inner surface of a monolithic module encompassing a LED including a sharp peak above

the LED and how such a shape of the inner surface may be arrived at will now be explained with reference to FIGS. 7-12. Since it is the re-directing functionality of a monolithic module similar to the module 615 that is described, such a module is in the following referred to as a "re-directing structure."

FIG. 7 provides a schematic illustration of an optical unit 700 used in the description of FIGS. 8-12. As shown, the optical unit 700 includes a LED 710 and a re-directing structure 715 having an inner surface 791 and an outer surface 792. In an embodiment, the LED 710 and the re-directing structure 715 could be analogous to the LED 610 and the module 615, respectively, described above and, therefore, their detailed descriptions are not repeated here.

While the inner surface 791 is shown in FIG. 7 as a dome, this is not relevant for the purpose of explaining the results shown in FIGS. 8-12 and, in fact, as explained below the shape of the inner surface 791 may be different. Similarly, while the outer surface 792 is shown to have a sandglass shape, this shape may also be different, depending on e.g. the desired radiation pattern. The inner surface 791 is merely shown to illustrate that "inner surface" is the surface of the re-directing structure 715 that partially encompasses the LED 710, while the outer surface 792 is shown to illustrate that "outer surface" is the TIR surface adapted to reflect light beams incident thereon by TIR. An angle between dashed lines 732 and 733 is referred to herein as an "embossing angle" of the re-directing structure 715.

In the discussions of FIGS. 8-12, the LED 710 is either considered to be a point source" emitter (i.e. all of the light beams emitted by the LED's die are considered to originate from a single point), which is illustrated in FIG. 7 with the LED 710 being a circle, or an "extended source" emitter (i.e., the light beams emitted by the LED's die are considered to originate not from a single point, but from different points of the emitting surface of the die), which is illustrated in FIG. 7 with the LED 710 being a dashed rectangle.

Coordinate system used in the explanations of FIGS. 8, 9, 11 and 12 is shown with the x-axis and the y-axis, where the point (0,0) of the coordinate system is considered to be at the center of the emitting surface of the LED 710 (be it a point source or an extended source emitter), the x-axis is used to indicate the position, in arbitrary units of length, and the y-axis is used to indicate thickness "t" of the re-directing structure 715, also measured in arbitrary units of length. As used herein, the term "thickness" of the re-directing structure 715 refers to the distance from the x-axis (typically from the substrate on which the LED 710 and the re-directing structure 715 are disposed) to the outer surface 792, measured in the direction of the y-axis. Thus, thickness t_{max} illustrated in FIG. 9 shows the point where the thickness of the re-direction structure 715 is at its maximum (thickness=max. thickness) and thickness t_0 illustrated in FIG. 9 shows the thickness of the re-directing structure 715 at its minimum, referred to herein as a "starting thickness" of a re-directing structure. For the sandglass-shaped re-directing structure illustrated in FIG. 9, the starting thickness happens to be measured along the axis of symmetry of the beam pattern of the LED 710 (i.e., above the center of the LED 710). The starting thickness may be given by e.g. the height of the LED chamber (i.e., the height of the dome 914 encompassing the LED die 912) and the minimum material thickness of the material of the re-directing structure 715 which has the necessary mechanical characteristics or is given by manufacturing reasons.

Note that, as used herein, the word "maximum" in the term "maximum thickness" refers to the thickness of the re-directing structure being at its maximum and that the "maximum thickness" is actually the minimum value of the thickness of

the re-directing structure that would allow all light beams incident on the outer surface 792 to be reflected with TIR.

Using Snell's law and light propagation laws, a set of appropriate trigonometric equations can be established describing the ray paths of light emitted at different angles from different spots on the emitting surface of the LED travelling to the boundaries formed by the inner and outer surfaces of the re-directing structure. Including information regarding refractive indices of the materials on different sides of the boundaries formed by the inner and outer surfaces and information regarding the shape of the inner surface in a manner known in the art, a shape of the outer surface 792 may be determined that would allow all of the light beams incident on the outer surface 792 to be reflected via TIR.

In the following discussions, the re-directing structure 715 is assumed to be made of a material having a refractive index n and to be surrounded by air (i.e., surrounded by a material having a refractive index equal to 1).

To calculate the outer surface just fulfilling the TIR conditions, starting point will be above the center of the LED 710. When the refractive index of the re-directing structure 715 is equal to 1.49 (e.g. the re-directing structure 715 is made from PMMA) and the LED 710 is considered to be a point source emitter, the embossing angle of the hourglass arrangement could be calculated to be equal to 95.7 degrees. The next coordinate points (x,y) of the outer surface can be calculated from

$$y(x)=t_0+\int_0^x \tan(\theta_{TIR}-\beta_{Ray})dx \qquad (1)$$

In equation (1), t_0 represents the starting thickness of the re-directing structure 715, θ_{TIR} is the minimum incident angle to fulfill TIR condition and β_{Ray} is the emission angle from the LED 710. For a point source located at (0,0), β_{Ray} is directly linked to the coordinates of the outer surface and the equation of the outer surface becomes:

$$y(x) = t_0 + \int_0^x \tan\left(\theta_{TIR} - \arctan\left(\frac{x}{y}\right)\right)dx \qquad (2)$$

FIG. 8 provides a computation result of the cross-section (x, y(x)) of such a shape of the outer surface 792 satisfying the TIR condition when the LED 710 is considered to be a point source emitter. In the simulation of FIG. 8, the re-directing structure 715 is such that the inner surface 791 forms a dome chamber encompassing the LED 710 or such that the LED 710 is immersed within the re-directing structure 715. As used herein, the term "immersed" is used to describe an embodiment where the inner surface 791 is in direct contact with the LED 710. As becomes clear from the inspection of the simulation result of FIG. 10, in this case, the outer surface 792 could as well be chosen to be essentially a parabola (with a minimum height to satisfy TIR condition) if the resulting light beam pattern after re-direction is meant to be essentially collimated.

The thinnest re-directing structure 715 above back plane based on the TIR condition (see equation (2) above), with starting thickness t_0 above the center of the LED 710, will have as maximum thickness of the re-directing structure 715:

$$\text{max. thickness}=t_0 e^{k\cdot\pi/2} \qquad (3)$$

where k=$\sqrt{1/(n^2-1)}$

However, the LED 710 cannot always be considered to be a point source emitter. This consideration becomes especially important when the size of the emitting surface of the LED 710 is comparable with the starting thickness of the re-direct-

ing structure **715**. For a LED **710** with a given size of the emitting surface (source_size), at a height h above the center of the LED **710** the incident angles (on the outer surface **792**) from the emitting surface will be distributed between

$$\pm \arctan\left(\frac{source\_size}{2h}\right),$$

which, at a height equal to the size of the emitting surface, will lead to emitting angles being distributed from −26 degrees to +26 degrees above the center of the LED **710**. This means that the embossing angle of the re-directing structure **715** would decrease to 55 degrees (for the re-directing structure **715** made from PMMA) to satisfy the TIR condition. As can already be made clear from a simple geometrical inspection of the relationship between the embossing angle and the maximum thickness of the re-directing structure **715** illustrated in FIG. **7**, the smaller the embossing angle, the greater the maximum thickness of the re-directing structure **715**. Thus, a decreased embossing angle leads to a significantly increased thickness of the re-directing structure **715** for the TIR condition to still be satisfied. Equation (2) would be changed here to include the extended source emission position to

$$y(x) = t_0 + \int_0^x \tan\left(\theta_{TIR} - \arctan\left(\frac{x - source\ size/2}{y}\right)\right) dx \qquad (4)$$

This case is illustrated in FIG. **9**, providing a computation result for a cross-sectional shape of the outer surface **792** satisfying the TIR condition when the LED **710** is considered to be an immersed extended source emitter (the dashed line in FIG. **9**). For comparison, the simulation result of FIG. **8** (i.e., the LED **710** is considered to be a point source emitter) is also included in FIG. **9** (the solid line in FIG. **9**).

When the LED **710** is considered to be immersed within the re-directing structure **715**, the solution for the maximum thickness of the re-directing structure **715** can still be written analytically, showing the dependence on source size and optics' size:

$$max \cdot thickness = \frac{t_0}{\sin\left(\frac{\pi}{2} - \arctan\left(\frac{source\ size}{t_0}\right)\right) e^{k\left(\frac{\pi}{2} - arctan\left(\frac{source\ size}{t_0}\right)\right)}} \qquad (5)$$

FIG. **9** illustrates that when only the outer surface **792** of the re-directing structure **715** is optimized to make sure that all light beams incident on the outer surface **792** are reflected by TIR, thickness of the re-directing structure **715** has to increase when the size of the emitting surface of the LED **710** is such that the LED **710** may no longer be considered to be a point source emitter. Just how big should the size of the emitting surface of the LED **710** be when it may no longer be considered to be a point source emitter is illustrated in FIG. **10**.

FIG. **10** illustrates dependence of the optics size on the size of the emitting surface of the LED **710**, where the term "optics' thickness" refers to the maximum thickness of the re-directing structure **715**. The x-axis in FIG. **10** is used to indicate the ratio between the starting thickness of the re-directing structure **715** (i.e., t_0) and the size of the emitting surface of the LED **710**, while the y-axis is used to indicate the

ratio between the maximum thickness of the re-directing structure **715** when the LED **710** is considered to be an extended source emitter and the maximum thickness of the re-directing structure **715** when the LED **710** is considered to be a point source emitter (i.e., the ratio between values calculated according to equation (5) and equation (3) provided above).

Point A in FIG. **10** illustrates that when the size of the emitting surface is approximately twice as large as the starting thickness of the re-directing structure **715** (i.e., the ratio depicted along the x-axis of FIG. **10** is equal to 0.5), the maximum thickness of the re-directing structure increases approximately 3 times compared with the maximum thickness necessary to satisfy TIR condition when the LED **710** can be considered to be a point source emitter. This means that when the ratio t_0/source_size is equal to 0.5, the re-directing structure **715** having a maximum thickness less than the value calculated according to equation (5), provided above, will not be able to satisfy TIR condition for all of the incident angles and some of the light will be leaked out.

FIG. **10** further illustrates that when the starting thickness of the re-directing structure **715** is increased with respect to the size of the emitting surface of the LED **710**, the ratio between the optics size for the extended source and a point source emitter decreases. Thus, as shown in FIG. **10** with a point B, when the starting thickness of the re-directing structure **715** is 2.5 times bigger than the size of the emitting surface of the LED **710**, the maximum thickness of the re-directing structure only needs to be increased approximately 1.25 times to satisfy the TIR condition in comparison with maximum thickness when the LED **710** could be considered a point source.

Point C in FIG. **10** corresponds to the scenarios depicted in FIG. **9** where the ratio between the starting optics' thickness and the source size is equal to 1.5 because in FIG. **9**, t_0 is shown to be equal to 1.5 units of length while the half of the extended source is shown to be equal to 0.5 units of length. FIG. **9** illustrates only a half of the extended source since, as described above, point (0,0) coincides with the center of an LED. As illustrated in FIG. **10** with point C, for such a ratio between the starting optics' thickness and the source size, the ratio between optics' thickness calculated for the extended source and for the point source is a little bit less than 1.5. This is also clear from comparing, in FIG. **9**, the maximum thickness of the dashed line and the maximum thickness of the solid line.

Based on FIG. **10**, it can be concluded that when the re-directing structure **715** is made thick enough, any LED **710** may be considered to be a point source and shape of the outer surface **792** may be determined so that TIR condition would be satisfied for all light beams incident thereon. However, as described in the background section, it may be desirable to make the re-directing structure **715** as thin as possible. To that end, employing a dome-shaped inner surface **791** (i.e., the inner surface **791** shaped so as to form a dome around the LED **710**) allows decreasing the overall thickness of the re-directing structure **715**, in comparison with the immersed LED described in FIG. **9**, while still satisfying the TIR condition. This is illustrated in FIG. **11**, providing a simulation result for a cross-sectional shape of the outer surface **792** satisfying the TIR condition when the LED **710** is considered to be an extended source emitter with the inner surface **791** forming a dome chamber encompassing the LED **710** (the dotted-dashed line in FIG. **11**). For comparison, the simulation results of FIG. **8** (i.e., the LED **710** is considered to be a point source emitter) and FIG. **9** (i.e., the LED **710** is consid-

ered to be an extended source emitter) are also included in FIG. **11** (the solid line and the dashed line, respectively, in FIG. **11**).

When the LED **710** is considered to be encompassed by a dome-shaped inner surface **791**, the solution for the maximum thickness of the re-directing structure **715** can no longer be written analytically. Instead, the equation for the outer surface **792** that would satisfy TIR condition for all incident beams, given the dome shape of the inner surface **791** needs to be solved numerically, which would read:

$$y(x) = t_0 + \int_0^x \tan\left(\theta_{TIR} - \arctan\left(\frac{x - x_c}{y - y_c}\right)\right) dx \qquad (6)$$

In equation (6), (x_c, y_c) are the coordinates of the ray's intersection with the dome interface before being incident on the outer surface in (x, y).

As is clear from FIG. **11**, employing a dome-shaped inner surface **791** allows decreasing the overall thickness of the re-directing structure **715** compared to the necessary minimum thickness for the immersed extended source scenario (dashed line in FIG. **11**) but the overall thickness is still significantly greater than that for the point sources scenario (solid line in FIG. **11**). Only by shaping the inner surface **791** beyond a dome shape, that is, by creating a peak above the LED **710**, can the light beams be sufficiently refracted at the inner surface boundary to be reflected by TIR at the outer surface **792**, without uncontrolled leakage and with minimum increase in the thickness of the re-directing structure **715**. When the inner surface **791** is shaped as shown in FIG. **6A** (such a surface may be referred to as 'peak-shaped' surface), then the numerical simulation similar to those shown in FIG. **11** would yield a shape of the outer surface **792** closest to the shape of the outer surface **792** for the point source scenario, i.e., with the minimum overall thickness of the re-directing structure **715**.

Similar to the dome-shaped inner surface, the solution for the maximum thickness of the re-directing structure **715** for the peak-shaped inner surface **791** cannot be written analytically, but may be obtained as a numerical solution.

To calculate the shape of the inner chamber, the inner surface's slope should be oriented so as to "rotate" the rays emitted from the edge of the source's surface into the direction of rays coming from the center (as the outer TIR surface was originally designed on that point). In other words, the inner surface slope should be oriented so that the rays emitted from the edge of the source's emitting surface would be refracted by the inner surface at such an angle that it would appear as if they were emitted from the center of the source's emitting surface. As used herein, the term "rotation" in the context of "rotation" of the rays emitted from the edge of the emitting surface is used to describe the change in the direction of such rays after they are refracted at the boundary with the inner surface due to the change in the shape of the inner surface.

The corresponding equation then becomes

$$n\sin(\alpha_{inner}(x_{inner}, y_{inner}) - \alpha_{target}(x_{inner}, y_{inner})) = \qquad (7)$$

$$\sin\left(\arctan\left(\frac{\text{source size}/2 - x_{inner}}{y_{inner}}\right) + \alpha_{inner}(x_{inner}, y_{inner})\right)$$

In equation (7), α_{inner} is the angle that the slope of the inner interface at coordinates (x_{inner}, y_{inner}) forms with the x-axis,

α_{target} is the target angle (i.e., angle as defined by rays emitted from the center position of the source) of the source's edge ray in the medium of refractive index n. The shape of the inner surface can then be integrated as

$$y_{inner}(x_{inner}) = y_0 - \int_0^{x_{inner}} \cot(\alpha_{inner}(x_{inner}, y_{inner})) dx \qquad (8)$$

In equation (8), y_0 is the starting height of the inner chamber above the center of the LED for the two-sided type redirecting structures as described here (i.e., the distance, measured in the direction of the y-axis, from the x axis to the peak of the inner chamber, such as the peak **638**). Note that, depending on the total source size/optics thickness ratio, when approaching the edge of the source, the slope increases such that the chamber will be reduced to zero thickness. To avoid this, the slope could be chosen smaller than necessary and the outer surface would need to be modified, leading to a slightly thicker solution of the optics. The thickness increase is, however, much less than with a dome-shaped inner surface, as the starting slope of the outer surface, above the center of the source, has been reduced significantly.

This is illustrated in FIG. **12**, providing simulation result of the cross-sectional shape of the outer surface **792** satisfying the TIR condition when the LED **710** is considered to be an extended source emitter with the inner surface **791** forming a peak shaped chamber encompassing the LED **710** (the dotted-dashed line in FIG. **12**, solution to the equations (7) and (8)). For comparison, the simulation results of FIG. **8** (i.e., the LED **710** is considered to be a point source emitter) and FIG. **9** (i.e., the LED **710** is considered to be an extended source emitter) are also included in FIG. **12** (the solid line and the dashed line, respectively, in FIG. **12**). This numerical simulation yields thus a shape of the outer surface **792** closest to the shape of the outer surface **792** for the point source scenario, i.e., with the minimum overall thickness of the re-directing structure **715**.

Persons skilled in the art will recognize that, depending on e.g. the final radiation pattern and mechanical constraints, the re-directing structure can be described by shapes different than the shapes illustrated in the exemplary embodiments herein. However, irrespective of the particular shape of the re-directing structure, reducing the otherwise steep embossing angle in the center above the LED is the most important consideration for the final thickness of the re-directing structure, when the LED is considered to be an extended source. The peak-shaped inner surface contributes efficiently to this reduction by "rotating" the incoming rays from the edge of the source into a direction that more easily can fulfill the TIR condition at the outer surface of the re-directing structure. The peak-shaped inner surface should have an average opening angle (such as e.g. the opening angle **639** illustrated in FIG. **6A**) so that, in a cross-sectional view like the one shown in FIG. **6A**, a straight line drawn between the peak **638** and the edge of the LED die **612** would not cross the inner surface **691**. For a starting height y_0 of the inner surface this condition reads:

opening angle=$2\alpha_{inner}(0, y_0)$=2 a tan(source size/2/y_0)

Further, to allow the "rotation" of the beam emitting from the edge of the source, the angle of the inner surface will be in the center for an inner surface starting height equal to the source size and for refractive index of n=1.49:

$2\alpha_{inner}(0, \text{source size})$=74 degrees (instead of 180 degrees as given for a dome shaped solution).

In practice, when a re-directing structure is manufactured by e.g. injection moulding, it could happen that the peak in the inner surface instead of being a sharp peak with an opening angle designed as described above is actually rounded on the very top (as shown in some exemplary structures illustrated in

FIG. **16**). In such a case the opening angle could be, in reality, equal to 180 degrees (because the peak itself forms a dome at the center of the inner surface of the re-directing structure). However, persons skilled in the art would still recognize that how to apply the teachings disclosed in the present invention regarding introducing an appropriate peak to the inner surface of a re-directing structure even when the peak is, in practice, rounded.

A second part of the inner surface can rather be given by mechanical constraint and minimum Fresnel reflection for rays already emitted from the LEDs in the final target direction. With these starting points in mind, optical raytracing software may be employed to find the overall compromise.

FIGS. **13A-13D** illustrate how, given the same maximum thickness and the same starting thickness of the re-directing structure **715** and the same shape of the outer surface **792**, light beams emitted from near the edge of the emitting surface of the LED **710** could be leaked out when a dome-shaped inner surface **791** is employed (see FIGS. **13B** and **13D**). In contrast, when a peak-shaped inner surface **791** is employed, the same light beams would be reflected at the outer surface **792** by TIR (see FIGS. **13A** and **13C**). Thus, shaping the inner surface **791** with respect to the outer surface **792** allows achieving that all of the light beams refracted at the inner surface **791** and incident on the outer surface **792** are reflected at the outer surface **792** by TIR.

Returning back to the optical unit illustrated in FIG. **6A**, for applications that require that some of the light is leaked out of the optical unit **600**, additional structures may be introduced to the module **615** that allow controlled light leakage in predetermined locations with respect to the LED **610**, according to one embodiment of the present invention. To that end, FIG. **14** illustrates a cross-sectional side view in the plane **250** of an optical unit **1400**, which is similar to the optical unit **600**. The optical unit **1400** includes a LED **1410** and a monolithic module **1415**, similar to the LED **610** and the module **615**, respectively, described above. Therefore, in the interests of brevity, a description of the LED **1410** and the module **1430** is not repeated here. The main difference between the optical unit **600** depicted in FIG. **6A** and the optical unit **1400** is that the latter also includes rings **1403** on an outer surface **1492** of the module **1415**. The rings **1403** are adapted to provide controlled leakage of a portion of light beams emitted by the LED **1410**. Alternatively or additionally, controlled leakage of light from the re-directing structure may also be achieved by introducing different corrugations in the outer surface of the module, as is schematically shown in FIG. **15**.

The embodiments described above have all illustrated the LED including a light emitting die covered with a dome. The optical units **600** and **1400** may also be implemented without including the domes **614** and **1414**. Instead, the monolithic module itself may be used to perform the functions of the dome over the light emitting die. In such embodiments, the monolithic module may be referred to as a "primary" optical component.

Further, optical units described above could also be made rotationally symmetric with respect to all angles and/or, while the illustrated embodiments are particularly advantageous for use with the top-emitting LEDs, the teachings of the present invention could also be applied for use with side-emitting LEDs.

In addition, while the embodiments described herein all include a sharp peak in the inner surface of the monolithic module, embodiments with the inner surface comprising a peak of a different shape are also within the scope of the present invention. FIG. **16** illustrates monolithic modules with inner surfaces comprising peaks of different shapes, according to various embodiments of the present invention.

While the description of the modified inner surface of a monolithic module was provided above with reference to the optical unit **200A**, considerations similar to those provided with respect to FIGS. **6A-16** could be applied to modify the optical units **200B** and **300** so that their inner surfaces would also include a peak. Since a person skilled in the art would easily recognize how to adapt the considerations provided with respect to FIGS. **6A-16** to other shapes of the monolithic module, detailed discussion of such adaptations is not necessary here.

While the forgoing is directed to embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof. Therefore, the scope of the present invention is determined by the claims that follow.

The invention claimed is:

1. An optical unit, comprising:

a light emitting device disposed on a surface; and

a monolithic module encompassing the light emitting device and comprising a re-directing portion and a first diffusing portion, wherein:

the first diffusing portion is configured to diffuse light incident thereon, and

the re-directing portion is configured to re-direct

at least a first portion of light emitted by the light emitting device to be incident on the first diffusing portion,

wherein the monolithic module includes an inner surface that forms a chamber in which at least part of the light emitting device is disposed and wherein at least a portion of the inner surface transitions from a concave structure to a convex structure.

2. The optical unit according to claim **1**, wherein the re-directing portion is further configured to re-direct a second portion of light emitted by the light emitting device to not be incident on the first diffusing portion.

3. The optical unit according to claim **2** wherein the second portion of light comprises less than 45% of the light emitted by the light emitting device.

4. The optical unit according to claim **1**, wherein the monolithic module further comprises a second diffusing portion, and wherein the re-directing portion is further configured to re-direct another portion of light emitted by the light emitting device to be incident on the second diffusing portion so that a projection of the re-directed first portion of light onto the surface and a projection of the re-directed other portion of light onto the surface form an angle between 0 degrees and 180 degrees.

5. The optical unit according to claim **1**, wherein the monolithic module is rotationally symmetric with an axis of symmetry of the monolithic module coinciding with an axis of symmetry of a beam pattern of the light emitting device.

6. The optical unit according to claim **1**, wherein the light emitting device comprises a light emitting die and a dome disposed over the light emitting die, and wherein the monolithic module is disposed over the dome.

7. The optical unit according to claim **1**, wherein the light emitting device comprises a light emitting die and the monolithic module is disposed immediately over the die.

8. The optical unit according to claim **1**, wherein the re-directing portion is configured to re-direct light by total internal reflection.

9. The optical unit according to claim **1**, wherein the first diffusing portion comprises diffusive material applied on parts of the re-directing portion.

10. The optical unit according to claim **9**, further comprising a diffusing cover configured to diffusively transmit light incident thereon, wherein the first diffusing portion is configured to diffusively reflect at least a portion of light incident thereon to be incident on the diffusing cover.

11. The optical unit according to claim **1**, wherein the monolithic module comprises an outer surface and wherein:

the inner surface is adapted to refract at least a first part of the first portion of light emitted by the light emitting device to be incident on the outer surface,

the outer surface is adapted to reflect the first part of the first portion of light incident thereon by total internal reflection, and

the inner surface comprises a peak.

12. The optical unit according to claim 11, wherein the inner surface is rotationally symmetric with an axis of symmetry of the inner surface adapted to coincide with an axis of symmetry of a beam pattern of the light emitting device, or the monolithic module is rotationally symmetric with an axis of symmetry of the monolithic module adapted to coincide with the axis of symmetry of the beam pattern of the light emitting device.

13. The optical unit according to claim 12, wherein, in a cross-section of the monolithic module, the cross-section including the axis of symmetry of the beam pattern of the light emitting device, the peak is at a point along the axis of symmetry of the beam pattern of the light emitting device.

14. The optical unit according to claim 1, wherein the concave structure is disposed between said convex structure and said surface on which the light emitting device is disposed.

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